USING TECHNOLOGY TO ADDRESS CLIMATE CHANGE

HEARING

BEFORE THE

COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HOUSE OF REPRESENTATIVES

ONE HUNDRED FIFTEENTH CONGRESS

SECOND SESSION

MAY 16, 2018

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May 16, 2018

USING TECHNOLOGY TO ADDRESS CLIMATE CHANGE

WEDNESDAY, MAY 16, 2018

HOUSE OF REPRESENTATIVES,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Committee met, pursuant to call, at 10:10 a.m., in Room 2318 of the Rayburn House Office Building, Hon. Lamar Smith [Chairman of the Committee] presiding.

LAMAR S. SMITH, Texas
CHAIRMAN

EDDIE BERNICE JOHNSON, Texas
RANKING MEMBER

Congress of the United States
House of Representatives
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

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Full Committee

Using Technology to Address Climate Change

Wednesday, May 16, 2018
10:00 a.m.
2318 Rayburn House Office Building

Witnesses

Mr. Oren Cass, Senior Fellow, Manhattan Institute

Mr. Ted Nordhaus, Executive Director, The Breakthrough Institute

Dr. Phil Duffy, President and Executive Director, Woods Hole Research Center

Dr. Judith Curry, President, Climate Forecast Applications Network; Professor Emerita, Georgia Institute of Technology

U.S. HOUSE OF REPRESENTATIVES
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

HEARING CHARTER

Wednesday, May 16, 2018

TO: Members, Committee on Science, Space and Technology

FROM: Majority Staff, Committee on Science, Space, and Technology

SUBJECT: Full committee hearing: "Using Technology to Address Climate Change"

The Committee on Science, Space, and Technology will hold a hearing titled *Using Technology to Address Climate Change* on Wednesday, May 16, 2018, at 10:00 a.m. in Room 2318 of the Rayburn House Office Building.

Hearing Purpose:

The purpose of the hearing is to examine climate change response policy. This hearing will emphasize the need for policy planning to account for technological developments designed to adapt to future conditions.

Witness List:

- **Mr. Oren Cass,** Senior Fellow, Manhattan Institute
- **Mr. Ted Nordhaus**, Executive Director, The Breakthrough Institute
- **Dr. Phil Duffy**, President and Executive Director, Woods Hole Research Center
- **Dr. Judith Curry**, President, Climate Forecast Applications Network; Professor Emerita, Georgia Institute of Technology

Staff Contact

For questions related to the hearing, please contact Majority Staff at 202-225-6371.

Chairman SMITH. The Committee on Science, Space, and Technology will come to order,

Without objection, the Chair is authorized to declare recesses of the Committee at any time.

Welcome to today's hearing titled "Using Technology to Address Climate Change." I'll recognize myself for five minutes for an opening statement and then the Ranking Member.

Today we will consider the use of technology to address climate change. We must take into account Americans' ability to develop innovations that will solve or mitigate challenges associated with climate change.

The climate is always changing, but what remains uncertain is the extent to which humans contribute to that change. What is certain is that human ingenuity will play a significant role in resolving future environmental issues.

Before we impose energy taxes or costly and ineffective government regulations, we should acknowledge the uncertainties that surround climate change research. Natural climate variability contributes to this uncertainty. Solar cycles, volcanic activity, El Niño/La Niña temperature fluctuations, and long-term oceanic circulation patterns are all naturally occurring events that have a major impact on the climate. Other unknowns such as the future of energy production and consumption also create uncertainty about future predictions.

Advanced nuclear reactors could change the landscape of both the developed world as well as developing economies.

Here's an example of an alarmist prediction not allowing for technological advances. A recent study found that the Intergovernmental Panel on Climate Change's worst-case scenario, which claimed further increasing emissions and temperatures, was based on outdated assumptions of coal usage. These assumptions didn't anticipate the American shale gas revolution and further undercut the reliability of the IPCC's findings.

In the field of climate science, there is legitimate concern that scientists are biased in favor of reaching predetermined conclusions. This inevitably leads to alarmist findings that are wrongfully reported as facts. Anyone who then questions the certainty of these findings is wrongly labeled a denier.

We will hear today about how the U.S. Government Accountability Office found that annual costs from worsening extreme weather events could increase as much as $112 billion annually by the year 2100. The GAO relied on studies that used outdated heat mortality rate statistics before the use of air conditioning became prevalent. This is a simple adaptation that would have changed the study's results dramatically.

Predicting economic and environmental conditions hundreds of years from now while ignoring humans' capacity to innovate and adapt is irresponsible. It is also intentionally misleading—the ultimate fake news. For instance, claiming that extreme weather will become more costly and deadly in the future as a result of climate change disregards inevitable advances in building materials and construction design. Instead of relying on big government to solve climate change problems, we should look to technological innovations that increase resilience and decrease vulnerability to inevitable climate change.

For decades, climate policy has focused solely on emissions reduction. Overreaching and costly regulations like the Obama Clean Power Plan do little to reduce emissions. Climate mitigating technologies are much more likely to benefit the environment. Similarly, non-binding international agreements with arbitrary temperature goals like the Paris Climate Agreement do not offer any realistic solutions and come at a high price to the taxpayer. Even if fully implemented by all 195 countries, which isn't and won't happen, it would only reduce global temperature by 0.3 degrees Fahrenheit over the next century.

Technology, though, provides the solution. Carbon emissions in the United States have decreased significantly over the last ten years thanks to fracking technology that has boosted access to affordable and clean burning natural gas.

Throughout our history, technology has always led the way. All major breakthroughs in transportation, medicine, communication, and space exploration have occurred because of scientific discoveries. Why wouldn't technology apply to climate change too?

Recognizing this, Microsoft founder Bill Gates and other high-tech giants recently put up $1 billion to find technology-related solutions. Together they launched Breakthrough Energy Ventures in 2016 to fund research into emerging energy and climate technologies. This is exactly the kind of innovative initiative we should encourage and support.

To solve climate change challenges, we first need to acknowledge the uncertainties that exist. Then we can have confidence that innovations and technology will enable us to mitigate any adverse consequences of climate change.

[The prepared statement of Mr. Smith follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
May 16, 2018

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement by Chairman Smith (R-Texas)
Using Technology To Address Climate Change

Chairman Smith: Today we will consider using technology to address climate change. We must ensure that our strategies take into account Americans' ability to develop innovations that will solve or mitigate challenges associated with climate change.

The climate is always changing, but what remains uncertain is the extent to which humans contribute to that change. What is certain is that human ingenuity will play a significant role in resolving future environmental issues.

Before we impose energy taxes or costly and ineffective government regulations, we should acknowledge the uncertainties that surround climate change research.

Natural climate variability contributes to this uncertainty. Solar cycles, volcanic activity, El Niño/La Niña temperature fluctuations and long term oceanic circulation patterns are all naturally occurring events that have a major impact on the climate.

Other unknowns such as the future of energy production and consumption also create uncertainty about future predictions.

Advanced nuclear reactors could change the landscape of both the developed world as well as developing economies.

Here's an example of an alarmist prediction not allowing for technological advances. A recent study found that the Intergovernmental Panel on Climate Change's (IPCC) worst case scenario, which claimed further increasing emissions and temperatures, was based on outdated assumptions of coal usage.

These assumptions didn't anticipate the American shale gas revolution and further undercut the reliability of the IPCC's findings.

In the field of climate science, there is legitimate concern that scientists are biased in favor of reaching predetermined conclusions.

This inevitably leads to alarmist findings that are wrongfully reported as facts. Anyone who then questions the certainty of these findings is wrongly labeled a "denier."

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The GAO relied on studies that used outdated heat mortality rate statistics before the use of air conditioning became prevalent. This is a simple adaptation that would have changed the study's results dramatically.

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For instance, claiming that extreme weather will become more costly and deadly in the future as a result of climate change disregards inevitable advances in building materials and construction design.

Instead of relying on big government to solve climate change problems, we should look to technological innovations that increase resilience and decrease vulnerability to inevitable climate change.

For decades, climate policy has focused solely on emissions reduction. Overreaching and costly regulations like the Obama Clean Power Plan do little to reduce emissions. Climate mitigating technologies are much more likely to benefit the environment.

Similarly, non-binding international agreements with arbitrary temperature goals like the Paris Climate Agreement do not offer any realistic solutions and come at a high price to the taxpayer. Even if fully implemented by all 195 countries, which won't happen, it would only reduce global temperature by 0.3 degrees Fahrenheit over the next century (according to Dr. Bjorn Lomborg).

Technology is what provides the solution. Carbon emissions in the U.S. have decreased significantly over the last 10 years thanks to fracking technology that has boosted access to affordable and clean burning natural gas.

Throughout our history, technology has always led the way. All major breakthroughs in transportation, medicine, communication and space exploration have occurred because of scientific discoveries. Why wouldn't technology apply to climate change too?

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To solve climate change challenges, we first need to acknowledge the uncertainties that exist. Then we can have confidence that innovations and technology will enable us to mitigate any adverse consequences of climate change.

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Chairman SMITH. That concludes my opening statement, and the gentlewoman from Texas, the Ranking Member, Ms. Johnson, is recognized for hers.

Ms. JOHNSON. Thank you very much, Mr. Chairman.

Let me start by expressing my disappointment that 16 months into this Administration, the Science Committee has yet to receive testimony from THE EPA Administrator, Scott Pruitt. Mr. Pruitt has appeared in front of multiple other committees multiple times. Yet, our repeated inquiries as to when we can expect Mr. Pruitt to appear in front of our committee have been met with unfulfilled assurances that a plan is in motion. By not inviting Mr. Pruitt to testify, we are—you are not only preventing this Committee from carrying out its oversight responsibilities, but you are preventing the American public from holding him accountable for his actions. It really is not too late. I ask you to commit today to holding a full Committee hearing before the August recess with Administrator Pruitt so that members on this Committee can do their jobs and get answers for the American people.

Today's hearing should be an opportunity to have a comprehensive discussion about the necessary climate adaptation and mitigation strategies our country needs to address climate change. Instead, today's hearing is a continuation of the Majority's seemingly unending attempts to call into question climate science and promote delay instead of action.

We will hear familiar stories from two of our witnesses who are making repeat appearances, one of whom who has testified numerous times in the past, espousing the same views on climate that we have heard before.

Climate is a complex and critically important issue. We cannot do good oversight if we only hear from those whom we have already heard.

Despite the title of this hearing, none of the witnesses invited by the Majority are themselves developers of technologies used in climate adaptation. Instead, the hearing seems to be focused on setting up a false policy choice between mitigation and adaptation strategies. In reality, adaptation and mitigation are not either/or solutions, and there is strong evidence to suggest that both adaptation and mitigation strategies are necessary.

The Risky Business Project, the Intergovernmental Panel on Climate Change, and the 2017 National Climate Assessment all recognize that near-term and long-term benefits from mitigation and long-term benefits from adaptation are mutually achievable.

Let me state this very clearly: the reality of climate change is inescapable. Our planet is warming, and human activity is a major driver of that warming. The visible impacts of climate change are everywhere, and while the Trump Administration has already set us on a backward trajectory when it comes to dealing with the causes of climate change, we must not permit a similar retreat when dealing with responses to climate change.

And let me just say before I yield the floor, I'd like to note that after six years with the Committee, Pamitha is leaving us to work for the Union of Concerned Scientists. He started on the Committee as an intern and was promoted over the years to press, then professional staff. So we thank him for all of his hard work and dedication, and we wish him well in his new position, and you can tell the scientists that we do support them.

Thank you, Mr. Chairman.

[The prepared statement of Ms. Johnson follows:]

OPENING STATEMENT
Ranking Member Eddie Bernice Johnson

House Committee on Science, Space, and Technology
"Using Technology to Address Climate Change"
May 16, 2018

Thank you.

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Let me state this clearly: the reality of climate change is inescapable. Our planet is warming, and human activity is a major driver of that warming. The visible impacts of climate change are everywhere, and while the Trump Administration has already set us on a backwards trajectory when it comes to dealing with the *causes* of climate change, we must not permit a similar retreat when dealing with *responses* to climate change.

Chairman SMITH. Thank you, Ms. Johnson.

The gentleman from Arizona, Mr. Biggs, the Chairman of the Environment Subcommittee, is recognized for his opening statement.

Mr. BIGGS. Thank you, Chairman Smith, for holding this important hearing to discuss climate change policy.

It is crucial that U.S. policy focuses on American technological innovation to address future environmental conditions.

Let me be very blunt: I firmly believe we must eliminate all costly, unjustifiable regulations and international agreements related to climate change from our policy agenda. President Obama's Clean Power Plan and the Paris Climate Agreement were estimated to cost billions annually, despite having a negligible projected impact on the environment. The Trump administration is rightfully putting an end to these egregiously pointless measures. Instead we should advance policies that encourage the development of technology to help mitigate and adapt to future environmental hazards, whether climate-related or otherwise.

To take just one example, hydraulic fracturing drove the shale gas revolution, which lowered U.S. carbon emissions in addition to boosting the national economy. No climate regulation can claim a similarly beneficial impact. Far from it.

The benefits or downsides of any new technology, such as fracking, cannot always be predicted when first developed. However, one thing we can count on is that humans will continue to innovate and find solutions to address pressing problems. Our capacity for ingenuity is something that cannot and should not be discounted. This ability to adapt through technology must be recognized by policymakers and scientists alike. For example, claiming with certainty that islands will be uninhabitable in 20 years because rising seas will eliminate access to drinking water, as one recent study has predicted, is grossly irresponsible. Not only is it an exaggerated and unrealistic prediction, it completely ignores the potential for innovations in land use and advancements in technology like water desalinization. Ignoring innovation effectively stifles further discoveries and technological advancements.

Assuming the status quo will remain in terms of technology and climate response ignores American ingenuity, which has driven economic progress and environmental improvements around the world. It would be foolish to craft policy in such a narrow-minded, stasis-reliant manner.

I look forward to testimony from our witnesses today that will identify the folly of climate alarmism and emphasize the need for a robust debate on the future of climate policy.

Chairman Smith, I thank you for holding this hearing, and I thank all of our witnesses for being here today, and I yield back the balance of my time.

[The prepared statement of Mr. Biggs follows:]

COMMITTEE ON
SCIENCE, SPACE, & TECHNOLOGY
Lamar Smith, Chairman

For Immediate Release
May 16, 2018

Media Contacts: Thea McDonald, Brandon VerVelde
(202) 225-6371

Statement by Rep. Andy Biggs (R-Ariz.)

Using Technology to Address Climate Change

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I look forward to testimony from our witnesses today that will identify the folly of climate alarmism and emphasize the need for a robust debate on the future of climate policy. I thank you all for being here today and yield back the balance of my time.

###

Chairman SMITH. Thank you, Mr. Biggs.

And the gentlewoman from Oregon, Ms. Bonamici, the Ranking Member of the Environment Subcommittee, is recognized for her statement.

Ms. BONAMICI. Thank you very much, Mr. Chairman and Ranking Member Johnson, and thank you to our witnesses for being here today.

Climate change is an important issue to our constituents and to our country. Today we should be having a robust conversation about climate adaptation and mitigation technologies and policies. We should not be using valuable time trying to discredit established scientific facts. The Science Committee should not be a forum where the human role in climate change is still debated. What would be best for our constituents would be working in a bipartisan manner to determine the best course of action to help them deal with the reality of a quickly changing climate.

The consequences of climate change are well known, and our understanding about how to address the causes of climate change continues to improve. We can no longer sit back and debate the merits of taking action. The time is now.

It's critical that we support scientific research about climate, and that we build on rather than break down decades worth of progress on this issue. Several of today's witnesses will try to present a false choice between climate adaptation and mitigation, but we know that these strategies go hand in hand.

In my home State of Oregon, devastating wildfires tore through the region last summer, endangering lives, harming local tourism, and resulting in significant losses for the timber industry. Although it is not possible to say that climate change causes a particular extreme weather event, we need to know more about how climate change increases the frequency and severity of these events.

Mitigation can provide near-term relief and help make sure communities are prepared to keep their families safe, but adaptation is necessary to address the larger issue of increasing frequency of severe weather events.

Coastal communities in Northwest Oregon are facing the consequences of ocean acidification, rising sea temperatures and levels, hypoxia, and other environmental stressors. Local shellfish growers and commercial fisheries are seeing the direct effects of climate change in their industries. Both mitigation and adaptation strategies can help people in the district I represent and across the country who are directly affected by droughts, rising sea levels, flooding, and severe weather.

The challenges of course are not unique to Oregon. In Alaska, for example, more than 30 towns and cities may need to relocate, costing hundreds of millions of dollars, because the permafrost is thawing and destabilizing the infrastructure.

These issues deserve attention. We should be directing more resources to the full range of potential solutions that are available, rather than continuing to debate whether humans contribute to climate change, which the rest of the world considers settled.

I am especially pleased that Dr. Phil Duffy from the Woods Hole Research Center is here to provide a scientific perspective on climate change and discuss the need for more federal research on global change. I also look forward to discussing the need for prompt action on climate adaptation and mitigation, rather than encouraging inaction with claims of uncertainty.

I hope the day comes soon when this Committee can talk about and work on bipartisan solutions to address the important issue of climate change.

And Mr. Chairman, as I yield back, I want to join Ranking Member Johnson in thanking Pamitha for his six years of dedication and good work to this Committee on Science, Space, and Technology, and I yield back.

Thank you, Mr. Chairman.

[The prepared statement of Ms. Bonamici follows:]

OPENING STATEMENT
Ranking Member Suzanne Bonamici (D-OR)
of the Subcommittee on Environment

House Committee on Science, Space, and Technology
"Using Technology to Address Climate Change"
May 16, 2018

Thank you Mr. Chairman and Ranking Member Johnson, and thank you to our witnesses for being here today.

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The consequences of climate change are well known, and our understanding about how to address the causes of climate change continues to improve. We can no longer sit back and debate the merits of taking action. The time is now. It is critical that we support scientific research about climate, and that we build on rather than break down decades worth of progress on this issue. Several of today's witnesses will try to present a false choice between climate adaptation and mitigation, but we know that these strategies go hand in hand.

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Thank you Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Ms. Bonamici.

And before I introduce our witnesses today, let me say that we are actually missing one individual, and she is not able to be with us. Her flight was canceled, not because of extreme weather, no, and this is Judith Curry, and we wish she had been able to come, but without objection, her written testimony will be made part of the record, and hopefully she'll be able to testify at another time.

[The prepared statement of Ms. Curry appears in Appendix II]

Chairman SMITH. Our first witness today is Mr. Oren Cass, a Senior Fellow at the Manhattan Institute, where he focuses on energy, environment, and anti-poverty policy. Mr. Cass was the Domestic Policy Director for Mitt Romney's presidential campaign in 2012. In this role, he helped shape campaign policy and communication on a variety of issues ranging from healthcare to energy to trade. Prior to joining the Manhattan Institute, Mr. Cass was a Management Consultant for Bain and Company, where he advised global companies on implementing growth strategies and performance improvement programs. Mr. Cass holds a bachelor of arts in political economy from Williams College and a juris doctor from Harvard University, where he was an Editor and the Vice President of the Harvard Law Review.

Our next witness is Mr. Ted Nordhaus, Founder and Executive Director of the Breakthrough Institute. He is a recognized author, researcher and political strategist in climate and energy policy. Mr. Nordhaus is the co-author of Breakthrough, the widely distributed book that was reviewed as "a vital strain of realism" by Time magazine. His opinion and editorial writings have been published in the Harvard Law and Policy Review, Wall Street Journal, New York Times, Scientific American, and other nationally distributed media. Over the years, Mr. Nordhaus has received the Green Book Award and Times' Heroes of the Environment Award. He holds a bachelor of arts in history from the University of California-Berkley.

Dr. Phil Duffy, our third witness, is President and Executive Director of Woods Hole Research Center. Prior to joining WHRC, Dr. Duffy served as a Senior Adviser in the White House National Science and Technology Council and as a Senior Policy Analyst in the White House Office of Science and Technology Policy. Before this, Dr. Duffy was the Chief Scientist for Climate Central, Inc. He has held senior research positions with Lawrence Livermore National Laboratory and visiting positions at the Carnegie Institute for Science and the Woods Institute for the Environment at Stanford University. Dr. Duffy was the recipient of the United Nations Association Global Citizen Award. He holds a bachelor's degree from Harvard University and a Ph.D. in applied physics from Stanford University.

We welcome you all. We appreciate your presence and your effort to get here. It wasn't easy for everybody. And Mr. Cass, if you'll begin?

TESTIMONY OF MR. OREN CASS,
SENIOR FELLOW,
MANHATTAN INSTITUTE

Mr. CASS. Thank you very much. Good morning, Chairman Smith, Ranking Member Johnson, and Members of the Committee, and thank you again for inviting me to participate in today's hearing. My name is Oren Cass. I'm a Senior Fellow at the Manhattan Institute for Policy Research, where my work addresses environmental policy including climate change economics.

My primary message to the Committee is this: The assumptions that we make about how human society will adapt to climate change are central to our understanding of the challenges the phenomenon presents and the costs that it will impose. Analyses that do not properly account for adaptation describe an alternative universe that does not exist. The estimates they produce are not plausible forecasts of future costs and should not be credited by policymakers.

Let me pause here to clarify that this issue does not concern climate science, and also to clarify that I would agree with the opening remarks that mitigation as well as adaptation is an important part of addressing climate change, and both of those points are addressed in my written testimony as well.

I believe policymakers should use mainstream climate science as the starting point for their work but we depart the world of climate science for that of climate economics when we turn to the question of how those changes will affect human society via their influence on public health or infrastructure or the economy.

The common failure to consider adaptation has profound consequences for how people conceptualize climate change, leading to what I call climate catastrophism. If the entire brunt of a century of climate change were to land on civilization tomorrow, the result might well be catastrophic, but if those changes occur gradually, as they are expected to, if they emerge in a world far wealthier and more technologically advanced than today's, as we expect it to be, and if policymakers ensure that people have the information and incentives to plan well, something over which we have control, then climate change will impose real costs but ones that we should have confidence in our ability to manage.

I'd like to briefly show what happens when we do this wrong and do not take account of adaptation properly. These are results of some recent studies that I describe the details of in my written testimony and which I'd be happy to answer questions about in more detail as well.

The first is from a study published in 2015 in Nature that looks at the relationship between year-to-year variations in temperature and year-to-year variations in economic growth across countries, and what they found was that there's a relationship. Some temperatures are better than others for growth, and they extrapolated that relationship out through the end of the century, essentially assuming that by the end of the century, countries will react every year to significantly warmer temperatures as if they came from out of nowhere.

What you're seeing here is the GDP per capita estimates produced by the study. You see essentially that China and India never grow wealthy because they become too warm. The United States does continue to grow, but by the end of the century has essentially flatlined, and if we begin to move higher up the chart, we reach Mongolia, which achieves per capita income roughly four times that of the United States, thanks to the warmer temperatures it would experience, or if we move even higher, we eventually reach all the way to Iceland at per capita incomes of $1.5 million, again because warmer temperatures would imply higher growth rates in perpetuity.

Now, these are obviously in some cases the outlying or extreme examples from the study but I think that that's the point, that if you don't consider the fact that these relationships will not simply hold unchanged, you end up with absurd results.

I'd like to look next at a study—excuse me, sorry, if we can skip to the next slide. Next slide. Thank you.

[Slide]

I'd like to look next at the GAO assessment of climate costs published last fall, which looked at two syntheses of costs to the United States. On the left is one published by the EPA, and on the right, one published by Rhodium. The Rhodium study finds most of its costs from extreme-heat deaths, literally it being so hot that tens of thousands of people die. The EPA study finds even higher costs from declines in air quality. And if we flip to the next slide, this is the EPA finding, that for both ozone and particulate matter, which have declined substantially in just the last 15 years, a very small uptick would essentially be the largest and in fact majority of all costs of climate change in the United States. This assumes that despite all progress to date, there is no further progress and we reduce pollution no more throughout the rest of the century.

[Slide]

And finally, if we flip to the last slide—this is my favorite—EPA looks at heat-related deaths and produces a chart that at first glance seems reasonable. Baseline in 2000, you see very small red dots, not a lot of deaths. By 2100, it's hotter and you see more deaths. But if you click ahead one click, notice what this implies, that the deaths in the North in 2100 will be dramatically higher than in the South in 2000, and if you flip ahead one more time, this is again the data on the EPA website showing that if we assume cities don't adjust in any way, deaths in places like Pittsburgh, Detroit, and New York will be 50 to 75 times the rate we see in Phoenix, Houston, and New Orleans today. This is obviously not what is going to happen. It's not a responsible way to connect economic analyses, and we should not be using it as the basis for policymaking.

Thank you very much.

[The prepared statement of Mr. Cass follows:]

Testimony of Oren M. Cass before the
House Committee on Science, Space, and Technology
May 16, 2018

Summary of Major Points

- Assumptions about how human society will adapt to climate change are central to our understanding of the challenges that the phenomenon presents and the costs that it will impose.
- This issue does not concern climate science but rather climate economics, which attempts to address the question of how the changes to our physical environment anticipated by climate science will affect human society via their influence on public health or infrastructure or the economy.
- In recent years, prominent studies that purport to forecast the cost of climate change have begun to rely on statistical analyses of the effects of temperature variation. These correlation-based, temperature-impact studies—"temperature studies"—start with present-day relationships between temperatures and outcomes such as mortality or economic growth. They extrapolate from those relationships a proportionally larger response to long-term projected climate warming and assign dollar values to the very large impacts that appear to emerge.
- The fallacies underlying this framework are (a) that the same responses detected for small, random variations in historical temperatures will manifest themselves proportionally in large, gradual, permanent future changes, and (b) that society will not change or adapt in any way to mitigate the effects.
- The GAO's 2017 report, "Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure," derives the vast majority of its costs from such studies, accepting absurd forecasts like one created by EPA that finds Pittsburgh's extreme-heat mortality rising to 75 times the level experienced in Phoenix or Houston today.
- Another emerging line of research seeks to link rising temperatures directly to changing rates of economic growth, again leading to bizarre predictions like Iceland and Mongolia becoming the world's leading economies while India's economy begins rapidly contracting. The Federal Reserve Bank of Richmond has recently published a working paper that uses a similar methodology.
- Analyses that do not properly account for adaptation describe an alternative universe that does not exist; the estimates they produce are not plausible forecasts of future costs and should not be credited by policymakers.
- Instead, policymakers should focus on understanding what adaptation is likely to be necessary, in what circumstances it will be difficult, and how better public policy can create the information and incentives to facilitate its occurrence.

Testimony of Oren M. Cass before the House Committee on Science, Space, and Technology May 16, 2018

Good morning Chairman Smith, Ranking Member Johnson, and Members of the Committee. Thank you for inviting me to participate in today's hearing.

My name is Oren Cass. I am a senior fellow at the Manhattan Institute for Policy Research where my work addresses environmental policy including the economics of climate change. This testimony focuses on the role that adaptation may play in the human response to climate change and the importance of accounting for such adaptation when conducting economic analyses of climate costs and when formulating climate policy. I addressed this topic recently in a Manhattan Institute report titled "Overheated: How Flawed Analyses Overestimate the Costs of Climate Change."[1]

My primary message to the committee is this: **The assumptions that we make about how human society will adapt to climate change are *central* to our understanding of the challenges that the phenomenon presents and the costs that it will impose.** Relative to most problems that we encounter in public policy, climate change is a gradual process; its most dangerous effects will appear on decades- and even centuries-long timescales. Yet analysts frequently analyze these effects as if they will happen *now*, without accounting for how our economy, society, and technology are likely to evolve independent of climate change and—especially—in response to climate change. **Analyses that do not properly account for adaptation describe an alternative universe that does not exist; the estimates they produce are not plausible forecasts of future costs and should not be credited by policymakers.**

Let me pause here to clarify that this issue does not concern climate science. I believe that mainstream climate science, particularly as summarized by the UN's Intergovernmental Panel on Climate Change, provides the best available assessment of the changes to our physical environment that a given level of greenhouse-gas emissions will cause and that policymakers should use it as the starting point for their own work. But we depart the world of climate science for that of climate economics when we turn to the question of how those changes will affect human society via their influence on public health or infrastructure or the economy.

[1] See Oren Cass, "Overheated: How Flawed Analyses Overestimate the Costs of Climate Change," Manhattan Institute for Policy Research, March 2018, https://www.manhattan-institute.org/html/overheated-how-flawed-analyses-overestimate-costs-climate-change-10986.html; see also Oren Cass, "The Problem with Climate Catastrophizing," *Foreign Affairs*, March 21, 2017, https://www.foreignaffairs.com/articles/2017-03-21/problem-climate-catastrophizing.

The common failure to consider adaptation has profound consequences for how people conceptualize climate change, leading to what I call *climate catastrophism*. If the entire brunt of a century of climate change were to land on civilization tomorrow—if a substantial share of agricultural output suddenly vanished, if sea levels were suddenly several feet higher, if regions accustomed to temperate summers suddenly experienced outdoor temperatures to which they were unaccustomed, if hundreds of millions of people were suddenly displaced—the result might well be catastrophic. But if those changes occur gradually (as they are expected to), if they emerge in a world far wealthier and more technologically advanced than today's (as we expect it to be), and if policymakers ensure that people have the information and incentives to plan well (something over which we have control), then climate change will impose real costs but ones that we should have confidence in our ability to manage.

* * *

The no-adaptation fallacy reaches its most concrete and absurd results in formal economic analyses of climate costs, and it is here that I want to focus your attention today. In recent years, prominent studies that purport to forecast the cost of climate change have begun to rely on statistical analyses of the effects of temperature variation. These correlation-based, temperature-impact studies—hereinafter referred to as temperature studies—start with present-day relationships between temperatures and outcomes such as mortality or economic growth. They extrapolate from those relationships a proportionally larger response to long-term projected climate warming and assign dollar values to the very large impacts that appear to emerge.[2]

A critical assumption underlying such an extrapolation is *ceteris paribus*, or "other things constant." The effect of small, random fluctuations in today's temperatures will only hold for large, gradual, permanent changes in future temperatures if no confounding factors exist and nothing in the world changes. For most economic studies, that construct is a valuable one. The whole point, typically, is to isolate the specific effect of one variable on another in the present. In estimating how additional years of education boost income, for instance, one need not worry that the labor market might look different eighty years hence.

In the climate context, however, this framework is wholly inappropriate. Given decades to respond to a gradual shift in temperatures, "other things" most certainly will not be "constant." Studies typically acknowledge that they assume no adaptation, but announcing a bad assumption does not make it a good one. They will sometimes argue that adaptation is unlikely to occur, by showing that it has not occurred in the past. But

[2] Most temperature studies, including those discussed here, acknowledge their failure to account for adaptation or caveat that their conclusions will not hold if adaptation occurs. Nevertheless, their no-adaptation findings are reported as credible estimates of future climate costs.

a failure to adapt to small, temporary changes says nothing about whether a society would adapt to large, permanent ones.

An adaptation may represent a cost-effective response to a large change in underlying climate but offer very little return on investment if implemented in response to a small change, or in response to unpredictable fluctuations. The failure to install an air conditioner for a year with one extra 90°F day, for instance, does not mean that air conditioners will not be installed in the face of 40 extra 90°F days annually. Adhering to a standard workday when the average temperature shifts from 82°F to 83°F does not rule out adjusting the workday, should the average reach 95°F.

Even where adaptations are immediately cost-effective, they may nevertheless be gradual. Social norms, economic configurations, and technologies emerge over time. Even if temperature fluctuations are enormous in magnitude, adaptations will be impossible where their implementation period is longer than that for which the condition lasts. People living in a location where the temperature swings annually by 10°F around an 80°F average may wish that it could sometimes have the permanent characteristics of a 70°F location and sometimes have those of a 90°F location, but that's not plausible; it will instead adapt to the behaviors optimal for an 80°F average with high variability. But if the underlying average shifts from 80°F to 90°F, a very different range of adaptations becomes likely.

The conceptual flaws of temperature studies are laid bare in the implausible outputs that they yield. Yet those outputs are accepted uncritically by the newsmedia and even the federal government, as reflected in last year's GAO report on climate costs—an assessment that relied overwhelmingly on such studies.

At the request of Senators Maria Cantwell (D., Washington) and Susan Collins (R., Maine), the GAO worked from December 2015 to September 2017 to review "the potential economic effects of climate change impacts and resulting risks to the federal government." Its report, "**Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure**" (hereinafter: *GAO*),[3] summarized two other studies that drew on and synthesized a further range of studies to provide national-scale estimates of the economic costs of projected climate change for the United States (see Figure 1).

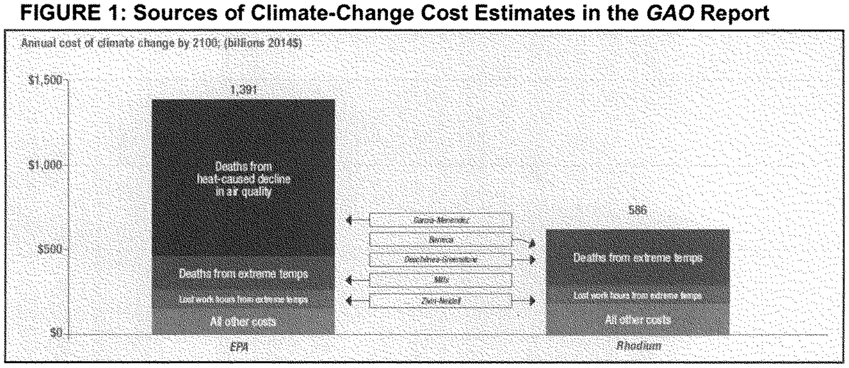
In both of these synthesis studies, the largest costs and vast majority of total costs derive from temperature studies that assert correlations between higher temperatures and more extreme-heat deaths, more air-pollution deaths, and fewer hours worked. The two synthesis studies *GAO* relied on are:

[3] U.S. Government Accountability Office, "Climate Change: Information on Potential Economic Effects Could Help Guide Federal Efforts to Reduce Fiscal Exposure," Sept. 2017, https://www.gao.gov/assets/690/687466.pdf.

- "**Climate Change in the United States: Benefits of Global Action,**" published in June 2015 by the U.S. Environmental Protection Agency (*EPA*).[4] This study estimates that by 2100, climate change annually will cost the U.S. $1.3 trillion–$1.5 trillion more than if aggressive action were taken to mitigate warming. At least 89% of this sum comes from temperature studies.

- "**American Climate Prospectus: Economic Risks in the United States,**" published in October 2014 by the Rhodium Group (*Rhodium*),[5] a research consultancy. This study estimates that by 2100, climate change will cost the U.S. $228 billion–$945 billion per year. At least 71% of this sum is based on the estimates from temperature studies.

FIGURE 1: Sources of Climate-Change Cost Estimates in the *GAO* Report



Note: Midpoints shown where analyses provide both high and low estimates. Rhodium reports estimates in 2011$, updated here to 2014$, using the U.S. Bureau of Economic Analysis GDP deflator. The *GAO* overview of *Rhodium* reports duplicative totals for "lost lifetime labor supply" and "storm losses," excluded here. *EPA* provides no 2100 estimate for power-systems savings; the 2050 value is used here. The *EPA* estimate understates sea-level impact by comparing it with a mitigation case in which sea levels still rise.

A review of the studies that account for the majority of costs provides a helpful view into how such studies are conducted and why they should be ignored. The following pages discuss, in turn, two studies used by *EPA* to produce its estimates of air-pollution and extreme-temperature mortality, and then two studies used by *Rhodium* to produce its estimate of extreme-temperature mortality.

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[4] U.S. Environmental Protection Agency, "Climate Change in the United States: Benefits of Global Action," June 2015, https://www.epa.gov/sites/production/files/2015-06/documents/cirareport.pdf. *EPA* includes $10 billion–$34 billion in energy-system costs reported for 2050; it provided no estimate for 2100.

[5] Robert Kopp et al., "American Climate Prospectus: Economic Risks in the United States," Rhodium Group, Oct. 2014, https://gspp.berkeley.edu/assets/uploads/research/pdf/American_Climate_Prospectus.pdf. *Rhodium* provides alternative measures for heat-related mortality and coastal impacts. The totals here use the methodologies that produced the highest cost estimates. Rhodium figures, as reported by *GAO*, use constant 2011 dollars. Figures here are updated to 2014 dollars.

The very fact that researchers are identifying small changes in air-quality and direct *deaths from heat* as the primary costs of climate change should indicate that something has gone wrong in how we are evaluating the issue.

The EPA *Assessment of Climate Costs*

The majority of all climate-related costs identified by *EPA* for the United States by the year 2100 derive from small changes in air quality; that study is discussed first. The second largest cost, from extreme-temperature deaths, is discussed second.

Pollution-Related Mortality: Fernando Garcia-Menendez et al., "U.S. Air Quality and Health Benefits from Avoided Climate Change Under Greenhouse Gas Mitigation," *Environmental Science & Technology* 49 (June 2015): 7580–88. (*Garcia-Menendez*)

Higher temperatures can interact with other environmental processes to change the atmospheric concentration of pollutants, even if pollutant emission rates do not change. For instance, ground-level ozone ("smog") gets worse on hot days. *EPA* tried to quantify these air-quality effects based on *Garcia-Menendez*. That study combined existing air-quality and climate-change models to forecast changes in atmospheric concentrations of ground-level ozone and particulate matter by 2100 if emissions remained constant but temperatures increased. It found that while concentrations would increase in some places and decrease in others, the average U.S. resident would be exposed to slightly increased levels of pollution: an increase of 3.2 parts per billion for ozone and 1.5 $\mu g\ m^{-3}$ (micrograms per cubic meter) for particulate matter (or, respectively, 2.6 parts per billion and 1.2 $\mu g\ m^{-3}$ greater than an alternative scenario in which climate change is aggressively fought).

Garcia-Menendez applied existing EPA formulas to these pollution increases to estimate that unchecked global warming would cost 57,000 lives per year in 2100, relative to an alternative scenario with aggressive action against global warming.[6] *EPA* assigned a value of $930 billion per year to those lives. The number of deaths seems alarming but appears much less consequential when placed in the context of present-day experience.

Here's why. The paper estimated that unchecked climate change would increase ozone levels by 2.6 parts per billion and particulate-matter levels by 1.2 $\mu g\ m^{-3}$, over the alternative scenario.[7] But those concentrations have fallen since 2000, from 82 and 13.4, respectively. In 2009 alone, particulate matter fell by an amount almost equal to the increase that climate change would cause over the century. In most of the years from

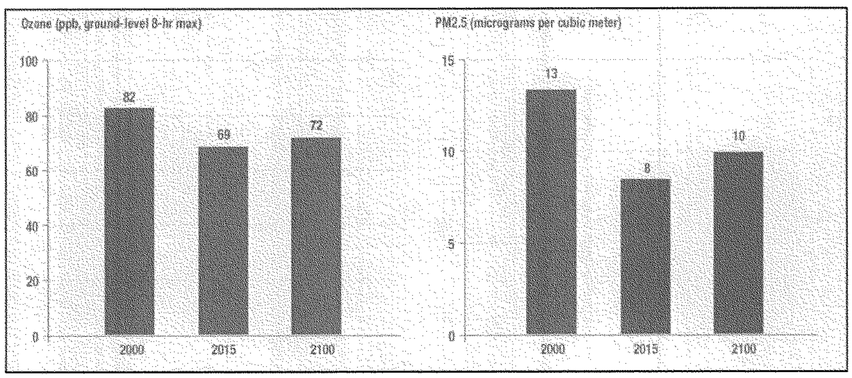
[6] *Garcia-Menendez*, Table 2.

[7] While *Garcia-Menendez* reports the effect of climate change on population-weighted concentrations, the underlying EPA data presented here on nationwide levels between 2000 and 2015 are not population-weighted.

2000 to 2015, ozone levels fluctuated by more than the climate-induced effect over a century.[8] Put another way, the forecasted effect of climate change on air pollution is to return atmospheric quality from 2015 to 2011 levels (see Figure 2).

Garcia-Menendez also implicitly assumes that recent decades' extraordinary pollution reductions will cease for the rest of the century and that no new technologies will reduce human exposure to pollution or its danger to health. In fact, ozone and particulate-matter levels for most of the country are already below thresholds that EPA deems safe, and those levels will almost certainly be far lower by century's end. In the context of a century of economic, social, technological, and environmental change, the identified impact of climate change on air pollution is barely noise. Yet it represents the majority of costs of all climate effects that *EPA* reports—$930 billion of $1,391 billion.[9]

FIGURE 2: Air-Pollution Concentrations in 2000, 2015, and 2100



Source: *Garcia-Menendez*; "Particulate Matter (PM2.5) Trends," U.S. Environmental Protection Agency; "Ozone Trends," U.S. Environmental Protection Agency.

<u>Temperature-Related Mortality:</u> David Mills et al., "Climate Change Impacts on Extreme Temperature Mortality in Select Metropolitan Areas in the United States," *Climatic Change* 131, no. 1 (July 2015): 83–95. (*Mills*)

The *EPA* estimate of costs due to additional heat deaths in 2100 relies on *Mills*. That study examined the effect on mortality rates from days of "extreme" heat (or cold) in 33 cities, defined, respectively, as days with a low temperature in the warmest 1% of the city's lows, or a high temperature in the coldest 1% of the city's highs. In Pittsburgh, for example, 99% of daily low temperatures were less than 21.7°C (71.1°F); a day with a

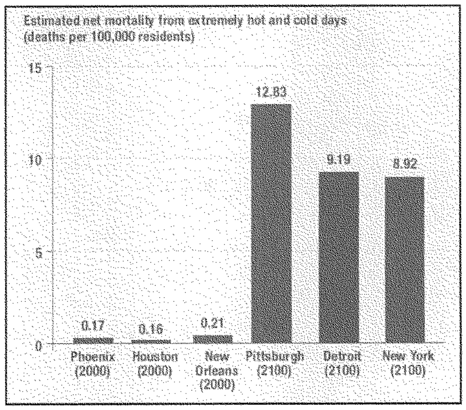
[8] "Particulate Matter (PM2.5) Trends," U.S. Environmental Protection Agency; "Ozone Trends," U.S. Environmental Protection Agency.

[9] *EPA*, pp. 78–79; see also *GAO*, p. 22.

warmer minimum temperature would count as "extremely hot."[10] For each city, the researchers measured the change in mortality on days with temperature extremes during 1989–2000.

Using climate models, the researchers then estimated for the years 2000 and 2100 a distribution of daily temperatures for each city. In 2000, the climate model's simulation of Pittsburgh had fewer than five extremely hot days;[11] for 2100, it had approximately 70,[12] each of which *Mills* assumed would have the elevated mortality level associated with extremely hot days in the past. Overall, *Mills* estimated that extreme-heat deaths in the 33 cities studied would rise from fewer than 600 in 2000[13] to more than 7,500 in 2100,[14] even if their populations remained constant.

FIGURE 3: Heat-Related Mortality in Select Southern Cities (2000) and Northern Cities (2100)



Source: The 2000 and 2100 city estimates come from the same *EPA* extrapolation of *Mills*. See *EPA*, Extreme Temperature, Figure 1.

EPA employed the *Mills* methodology but used a different climate model to forecast the increase in extremely hot days, applied the work to additional cities, and accounted for population growth over the century.[15] In the *EPA* model, Pittsburgh's annual death rate from extreme temperatures increases 30-fold, from 0.4 per 100,000 people in 2000 to 12.8 in 2100.[16] Across all cities, excess fatalities by 2100 would exceed 12,000.

The *Mills* estimates of heat deaths provide a quintessential illustration of the flaw in an assumption of no adaptation. The study uses historical data to predict the response to temperature variation 100 years later, which presumes that society's reaction to a given variation will be the same at both points in time. That assumption is a poor one.

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[10] *Mills*, Online Resource 1.

[11] *Mills*, Online Resource 2.

[12] *Mills*, Online Resource 5.

[13] *Mills*, Online Resource 3.

[14] *Mills*, Table 2.

[15] E-mail correspondence with David Mills, Jan. 17, 2018. See *EPA*, "Extreme Temperature," n. 29, for discussion of *EPA*'s extension of the *Mills* model to additional cities.

[16] *EPA*, "Extreme Temperature," Figure 1.

If global warming makes heat currently regarded as extreme more frequent and less surprising, then temperate cities will almost certainly make adaptations to function better in heat, much as people moving to cities in warmer climates have already done. But *Mills* assumes, implausibly, that an anomalous temperature in 2000 does the same harm as an equal, but by then less anomalous, temperature in 2100.

The implausibility of the no-adaptation assumption is most obvious in the single-city mortality estimates it produces. *EPA* uses the model in *Mills* to estimate 12,000 annual heat deaths nationally in 2100. Much of the estimate stems from temperature increases in northern cities such as Pittsburgh, Detroit, and New York, with forecasted heat-related mortality rates of 12.8, 9.2, and 8.9 per 100,000. Yet southern cities such as Phoenix, Houston, and New Orleans, which were already hotter in 2000 than northern cities are predicted to be in 2100, had mortality rates in 2000 of only 0.2 per 100,000 (see Figure 3).

Mills explained that its main findings "explicitly exclude consideration of the possibility of there being an adaptive response over time to extreme temperatures." Still, *Mills* did provide an alternative analysis in which every city increases its extreme-heat threshold to that of present-day Dallas. With this alternative assumption, extreme-heat deaths fell by almost two-thirds.[17] *EPA* did not use this result.

The Rhodium *Assessment of Climate Costs*

In sharp contrast to *EPA*, *Rhodium* did not incorporate any cost estimate for air pollution into its analysis; temperature-related mortality thus plays a much larger role. *Rhodium* used two different studies to develop its cost estimate for temperature-related mortality. The first, which applied a historical mortality rate to future warming, pointed toward a very high cost estimate. The second focused specifically on adaptation and found that Americans have become well-adapted to extreme heat thanks to air-conditioning. But *Rhodium* concluded anyway that climate change will cause tens of thousands of American deaths each year by century's end, leaving its discussion of future adaptation to a separate chapter that did not inform its top-line cost estimate.

Temperature-Related Mortality: Olivier Deschênes and Michael Greenstone, "Climate Change, Mortality, and Adaptation: Evidence from Annual Fluctuations in Weather in the US," *Applied Economics* 3, no. 4 (Oct. 2011): 152–85. (*Deschênes-Greenstone*)

Deschênes-Greenstone underlies the *Rhodium* estimate of heat deaths due to warming. This study used an approach different from that of *Mills*; it grouped temperatures into 10-degree-Fahrenheit buckets (70°–80°F, 80°–90°F, >90°F, etc.), counted the days with

[17] *Mills*, Table 2.

average temperatures at each level in each U.S. county in each year during 1968–2002, and compared these counts with total mortality rates in each county and year. The researchers found that an additional very cold (<30°F) or very hot (>90°F) day was associated with 0.5–1.0 additional deaths per 100,000 people.[18]

Like *Mills*, *Deschênes-Greenstone* used climate models to estimate the temperature distribution at the end of the century. Their analysis found that climate change would reduce cold-related deaths somewhat but increase heat-related deaths much more. The average county saw one >90°F day each year during 1968–2002 but would see 44 such days each year during 2070–99.[19] If the danger of experiencing a daily temperature within a given bucket did not change, the result of climate change would be 123,000 more heat-related deaths and 59,000 fewer cold-related deaths each year, for a net impact of 63,000 additional deaths by 2100 (totals do not sum due to rounding).[20]

Unlike *Mills*, *Deschênes-Greenstone* focuses on an absolute threshold of >90°F for an extremely hot day, valid for all locations and times. Whereas *Mills* assumes that the ability to cope with high temperatures is location-specific and does not change with climate, *Deschênes-Greenstone* assumes that certain temperatures are more costly everywhere and always.

This approach has the virtue of allowing the researchers to consider more carefully the effects of climate adaptation because it can compare the future effects of global warming—for example, higher temperatures in northern cities—with conditions that exist today, such as temperatures in southern cities, and thereby assess whether cities in already-hot climates have already made adaptations. Technological advances may further improve adaptation to hot weather, but if a study can at least show that present-day adaptations do not improve hot cities' resilience, it can better justify high estimates of global warming's harms.

Deschênes-Greenstone conducted several useful analyses to test for adaptation and found that absolute extreme heat worsened mortality in both hotter and colder climates. Yet their conclusion was undermined by a subsequent paper—which is also cited by *Rhodium*, and of which Deschênes and Greenstone themselves are coauthors.

<u>Temperature-Related Mortality:</u> Alan Barreca et al., "Adapting to Climate Change: The Remarkable Decline in the US Temperature-Mortality Relationship over the Twentieth Century," *Journal of Political Economy* 124, no. 1 (Feb. 2016): 105-59. (*Barreca*)

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[18] *Deschênes-Greenstone*, Figure 2.

[19] *Deschênes-Greenstone*, Table 1.

[20] *Deschênes-Greenstone*, Table 5.

Rhodium also cites *Barreca*[21] for its calculation of extreme-temperature deaths. But rather than focus on projecting deaths from extreme temperature in the future, *Barreca* demonstrates the extraordinary reduction in such deaths in the past. *Barreca* found that the lethality of temperatures above 90°F fell by 80% from the first to the second half of the 20th century, thanks primarily to the adoption of residential air-conditioning. This trend continued even within the second half of the 20th century, with the mortality effect falling by half from the 1960–79 period to the 1980–2004 period.[22]

The researchers concluded that air-conditioning "has positioned the United States to be well adapted to the high-temperature-related mortality impacts of climate change." Applying the *Deschênes-Greenstone* estimate of 42.3 additional >90°F days by 2100, they estimated that climate change could cause roughly 60,000 additional deaths in 2100 at the 1960 level of air-conditioner adoption. But at the 2004 level of air-conditioner adoption, "the null hypothesis that additional 80°F–89°F and >90°F days would have no impact on mortality cannot be rejected." Or, to put this in plain English: additional extremely hot days could mean zero additional heat deaths.

Eliminating the extreme-heat estimate from *Deschênes-Greenstone*, or even reducing it to the statistically insignificant estimate provided in *Barreca*, raises another possibility: climate change could reduce extreme-temperature mortality. *Deschênes-Greenstone* estimated nearly 60,000 cold-related deaths avoided (specifically, a 2.8% reduction in the mortality rate), offset by twice as large an increase in heat-related deaths (a 5.8% increase in the mortality rate).[23] Yet with *Barreca*'s lower estimate of heat-related costs (only a 1.5% increase in the mortality rate by the 1990–2004 period),[24] the cold-related benefits would dominate. Climate change would reduce mortality by roughly 28,000 lives annually (see Figure 4).

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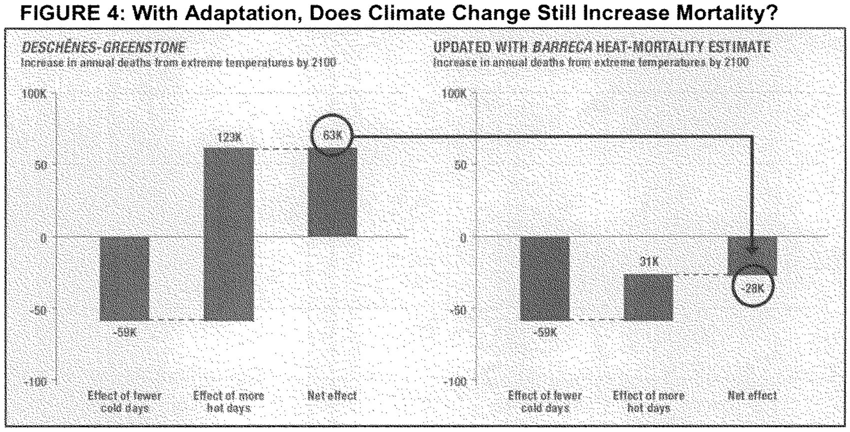
[21] The version of *Barreca* cited here is the paper published in its final form after the release of *Rhodium*. *Rhodium* cites a substantively comparable version of the paper released in Jan. 2013 as an NBER working paper.

[22] *Barreca*, Figure 3.

[23] *Deschênes-Greenstone* presents its final mortality estimates for both increased heat-related deaths and decreased cold-related deaths in Table 5 (cols. 1a–1c). The net effect, an increase of 63,000 deaths, translates to a 3.0% increase in the mortality rate (col. 4).

[24] The suggestion to translate the *Barreca* estimate into terms comparable with the *Deschênes-Greenstone* estimate, as well as the technique for doing so, comes from one of the study's authors (e-mail correspondence with Olivier Deschênes, Dec. 20–22, 2017). The *Barreca* point estimate of 0.0021 for 1990–2004 is divided by six (to account for its two-month exposure window) and multiplied by 100 to give the percentage change in mortality per >90°F day, and then multiplied by 42.3 additional days to give a mortality increase equivalent to those discussed in *Deschênes-Greenstone*. The *Rhodium* authors use a similar process to convert the *Barreca* analysis into terms comparable with *Deschênes-Greenstone*; see Solomon Hsiang et al., "Estimating Economic Damage from Climate Change in the United States," *Science* 356, no. 6345 (June 30, 2017): 1362–69, Supplemental Material, B.3. Given the differences in the *Deschênes-Greenstone* and *Barreca* methodologies and data sets, combining their outputs provides only a rough estimate. The approach is used here to illustrate the large effect of accounting just for already-exhibited adaptation; a full reanalysis would be required to produce a new point estimate.

FIGURE 4: With Adaptation, Does Climate Change Still Increase Mortality?



Rhodium acknowledges *Barreca*'s finding but declines to employ it, instead combining the *Deschênes-Greenstone* and *Barreca* analyses in a way that projects a substantial increase in mortality, while deferring discussion of adaptation to a separate chapter and excluding it from the main cost estimates.[25] If *Rhodium* had used the extreme-temperature mortality decrease that *Barreca*'s adaptation finding implies, rather than forecasting a mortality increase, its total climate-cost estimate would fall by more than 90%.[26]

The Mongolian Century

Temperature studies have progressed even beyond the framework described above, in which temperature is linked to public health; the next frontier establishes an abstract link from temperature directly to economic growth, finding that warmer temperatures slow growth and so climate change could cause the global economy to stall.

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[25] *Rhodium*, p. 63; the discussion of adaptation on p. 166 estimates that the effect would remain negative but reduces the magnitude by approximately half.

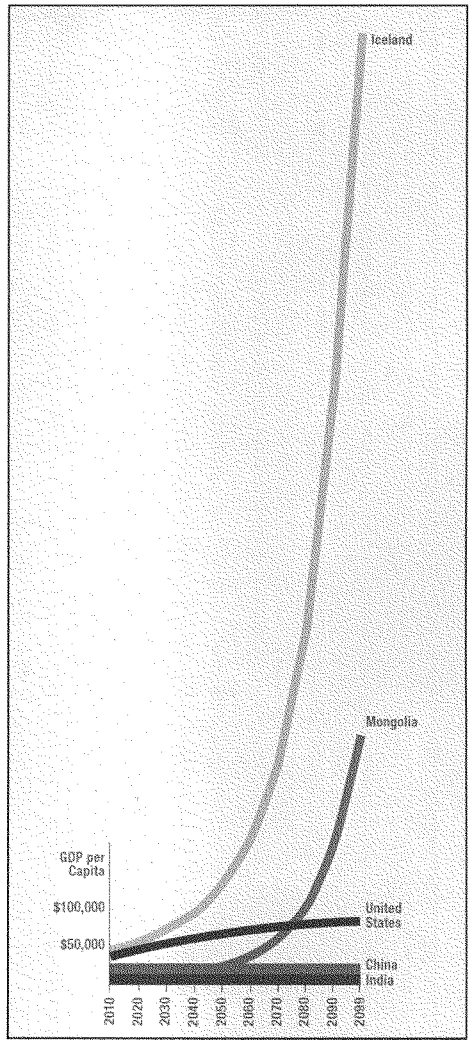
[26] *Rhodium* uses a value-per-life of $7.9 million to yield a midpoint cost estimate of $298 billion (see p. 108), implying roughly 37,000 total excess fatalities. If that were instead 28,000 fewer fatalities, the benefit would be $222 billion. This would change the total estimated cost in *Rhodium* from $557 billion to $36 billion ($586 billion to $38 billion in 2014$).

Marshall Burke, Solomon Hsiang, and Edward Miguel, "Global Non-Linear Effect of Temperature on Economic Production," ***Nature*** **527 (Nov. 2015): 235-39. (*Burke*)**

Burke compares year-to-year variations in a country's average temperature with variations in those same years in economic growth, controlling for associated changes in precipitation. It found that in countries with average temperatures below 13°C (55°F, about the average temperature of Baltimore, Milan, Beijing, or Wellington), growth was better in warm years; countries with higher average temperatures saw better growth in cool years.

Burke theorizes that these short-term fluctuations evinced a universal effect of temperature on growth: every country would see its maximum growth (determined by non-meteorological factors) at a 13°C average temperature—a dynamic that will not change as the climate warms. To extrapolate from this relationship to a possible effect of climate change, *Burke* constructs a model in which every country's baseline temperature is its average during 1980–2010 and its baseline rate of economic growth is that forecasted by the Shared Socioeconomic Pathway (SSP, a widely used set of national GDP predictions that assumes a stable climate). The difference between the baseline temperature and temperature forecasted in some

FIGURE 5: Projected GDP per Capita Following Climate Change



Source: *Burke*; replication data available at https://web.stanford.edu/~mburke/climate/data.html, "Projected per capita GDP with climate change (based on SSP5 and RCP8.5), 2010–2099."

future year by a climate model provides the variation used to predict how growth in that year will vary from the SSP forecast.

Let's say that a country's gradual warming raises its temperature from, for example, 15°C during 1980–2010, to 19°C in 2100. The model attempts to predict the effect on economic growth of a 15°C country experiencing a sudden 19°C year. But the economic performance of other countries with a present-day 19°C average is ignored. The shift in the country's own long-run average is ignored.

Burke builds a modified set of SSP growth forecasts that accounts for the effect of warmer temperatures on every country in every year, and concludes that global warming will reduce per-capita gross world product (GWP) by 23% by 2100.[27]

Projecting each location's response to a century-long temperature change on the basis of how locations reacted to small variations from their own averages in the past produces extremely dubious, if not preposterous, results. *Burke*'s model takes normal economic growth in cold or hot countries as a sign not of economic specialization to a local climate but of often stupendous underlying growth potential that the local climate suppresses.

Burke forecasts that Mongolia, whose per-capita income of $861 made it the 118th wealthiest country in 2010, will leap to seventh in 2100, with a per-capita income of $390,000—more than four times America's projected per-capita income of $90,000. Iceland achieves a per-capita income of $1.5 million, more than twice that of any other country besides Finland ($860,000), with annual economic growth above 5% and accelerating (see Figure 5). Canada's economy becomes the world's second-largest (behind only the U.S.), nearly seven times larger than China's.

Conversely, *Burke* expects India to be the world's poorest country in 2100, with per-capita income no higher than in 2030 and declining at almost 4% per year. It expects Israel, the country that made the desert bloom (and found itself with a water surplus during the intense drought that some consider a catalyst for Syria's civil war), to have a per-capita income in 2100 similar to its 2010 level and declining at more than 2% per year.[28]

Perhaps we should accept that a 23% loss in global per-capita income is plausible, however dramatic. But the model's country-specific outputs are irreconcilable with any plausible understanding of the determinants of economic growth and the potential

[27] For comparison, this estimate is an order of magnitude larger than the cost of 1%–4% of GDP estimated by the Obama administration in its "Social Cost of Carbon" analysis; see Figure 1B in "Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis—Under Executive Order 12866," Interagency Working Group on Social Cost of Carbon, Feb. 2010.

[28] The authors provide country-specific model results at https://web.stanford.edu/~mburke/climate/data.html; see "Projected per capita GDP with climate change."

course of economic development in the coming century. It might seem unfair to hold the study accountable for its least reasonable-seeming implications. Sure, the results for Iceland and Mongolia are wrong, but how much can that matter if they contribute little to the ultimate result? That is the wrong way to analyze the issue. Either one believes the premise that gradual shifts in temperature will drive economic growth on the basis of the curve that *Burke* derives, or one does not. If a statistical model makes easily falsifiable predictions, it is a bad model.

To believe *Burke*, one must believe that a gradual rise in average temperature from 0° (32°F) to 5°C (41°F) will turn Iceland and Mongolia into the leading economies of the 21st century. The more plausible conclusion is that responses to large, gradual temperature changes are qualitatively unlike responses to small temperature fluctuations and that the entire enterprise in *Burke*, as in other adaptation-ignoring temperature studies, is flawed.

Burke attempts to defend its assumption of no adaptation by showing that countries responded similarly to short-term temperature fluctuations before and after 1990, suggesting that no adaptation has occurred to date. It also finds that rich and poor countries responded similarly, suggesting that future wealth will not insulate countries from the effects of warming. But such findings say nothing about whether relationships identified for fractional-degree variations can be extrapolated to multiple degrees of warming, or how countries will respond to not just yearly fluctuations but changes in their own underlying baselines.

Analyses like *Burke* will likely proliferate as researchers employ the same statistical techniques to generate large estimates of climate costs in a variety of contexts. For instance, earlier this year the Federal Reserve Bank of Richmond published a working paper that applied a similar methodology across U.S. states and found that climate change "could reduce U.S. economic growth by up to one-third over the next century."[29]

Such a finding is particularly bemusing because, as the authors acknowledge, the effect is largest in southern states—ones that have shown strong economic growth in recent years. Reporting on the findings, the *Wall Street Journal* observed, "their projections partly reflect the emergence of the southern U.S. as a major contributor to national economic growth. As overall temperatures rise, they'll hit that already warm zone hard."[30] Americans are moving in large numbers to the nation's warmest states, and

[29] Riccardo Colacito et al., "Temperature and Growth: A Panel Analysis of the United States," *Federal Reserve Bank of Richmond*, Working Paper 18-09 (Mar. 2018), https://www.richmondfed.org/-/media/richmondfedorg/publications/research/working_papers/2018/pdf/wp18-09.pdf.

[30] Michael S. Derby, "Climate Change May Deeply Wound Long-Term U.S. Growth, Richmond Fed Paper Finds," Wall Street Journal, May 2, 2018, https://blogs.wsj.com/economics/2018/05/02/climate-change-may-deeply-wound-long-term-u-s-growth-richmond-fed-paper-finds/.

such states have exhibited especially robust economic performance, and somehow this *compounds* rather than refutes the concern that warm temperatures will lead unavoidably to economic stagnation.

* * *

The flaws in these temperature studies do not mean that researchers should abandon estimates of the future costs of human-caused climate change. There is every reason for policymakers to continue to carefully consider legitimate cost estimates. So, too, researchers should continue to study the concrete effects of absolute changes in temperature and the nature of associated adaptation, as these findings help to identify which climate-related threats are the most severe and which adaptations may require changes in public policy.

For example, continued research on sea-level changes and their implications for coastal development will be invaluable to responsible public policy in the decades to come. In *Deschênes-Greenstone*, the authors also study the effects of extreme temperatures on energy consumption and show that it (and the associated cost) rises significantly. Just because adaptation is desirable and likely to occur does not make it free.

Policymakers should work to ensure that society has the best possible <u>information</u> about likely effects of climate change and the right <u>incentives</u> to take that information into account. Specifically:

- Continue to invest in climate science. If decision-makers from urban planners to farmers to coastal property owners are to make intelligent investments that build resilience and adapt to changes in climate, they will need the best possible forecasts of what those changes are likely to be.

- Focus research directly on adaptation. Rather than accept the convenience of modeling a future without adaptation, emphasize the need for better understanding of adaptation pathways: Where will it occur naturally? Where will it occur but at a cost or only with better policy? In what situations might adaptation be insufficient and what contingency planning is required? Understanding the answers to those questions will highlight the costs that are most concerning and point toward the policy responses that might be most effective.

- Ensure that decision-makers have the right incentives to account for climate change and its costs. If government insulates people from the costs of climate change, they will not have sufficient incentive to prepare for the costs or avoid them. Insurance products must accurately reflect risk; the price of water must reflect its supply and demand; urban planners must understand their own cities will be responsible for upgrading infrastructure that they build unwisely.

Finally, the prospect of adaptation to climate change does not mean that mitigation is unimportant. Ultimately, greenhouse-gas emissions must decline if atmospheric concentrations are to stabilize. Low-cost, low-carbon energy technologies therefore remain vital and Congress should continue to fund research and development in this area. Congress should also review its use of subsidies, which today serves primarily to prop up wind and solar industries that have had decades to become competitive. Subsidies should be time-limited for a given technology, to keep innovation focused on solutions with the potential to out-compete fossil fuels in the market—especially in the developing world.

Thank you again for the opportunity to appear before the Committee. I hope my testimony will be helpful to you as you assess economic analyses of, and consider appropriate federal responses to, climate change.

Biography for Oren M. Cass

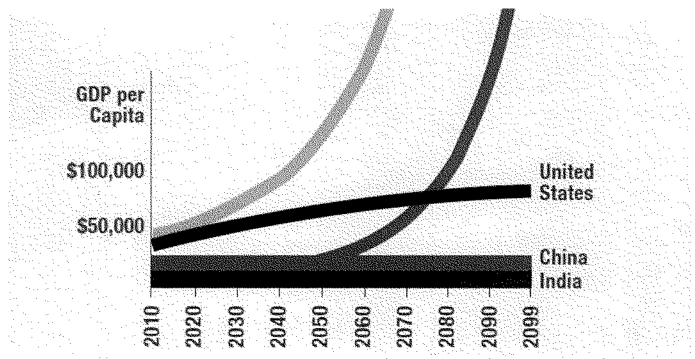
Oren Cass is a senior fellow at the Manhattan Institute, where he focuses on energy, the environment, and antipoverty policy. He has written about climate change for publications including the *Wall Street Journal* and *Foreign Affairs*, testified before House and Senate committees, briefed EPA and White House officials, spoken on campuses including MIT and the University of Texas, and appeared on national and international media including NPR and the BBC. An archive of his published work is available at http://www.orencass.com.

In 2011–12, Cass was the domestic policy director for Mitt Romney's presidential campaign, where he shaped campaign policy and communication on issues from health care to energy to trade. Prior to joining the Manhattan Institute, Cass was a management consultant for Bain & Company in the firm's Boston and New Delhi offices, where he advised global companies across a range of industries on implementing growth strategies and performance-improvement programs.

Cass holds a B.A. in political economy from Williams College and a J.D. from Harvard University, where he was an editor and the vice president of volume 125 of the *Harvard Law Review*.

[Slides]


HOUSE COMMITTEE ON SCIENCE, SPACE, & TECHNOLOGY
HEARING: USING TECHNOLOGY TO ADDRESS CLIMATE CHANGE
MANHATTAN
INSTITUTE
Oren Cass
Senior Fellow
May 16, 2018


GDP per Capita
$100,000
$50,000
United States
China
India
2010
2020
2030
2040
2050
2060
2070
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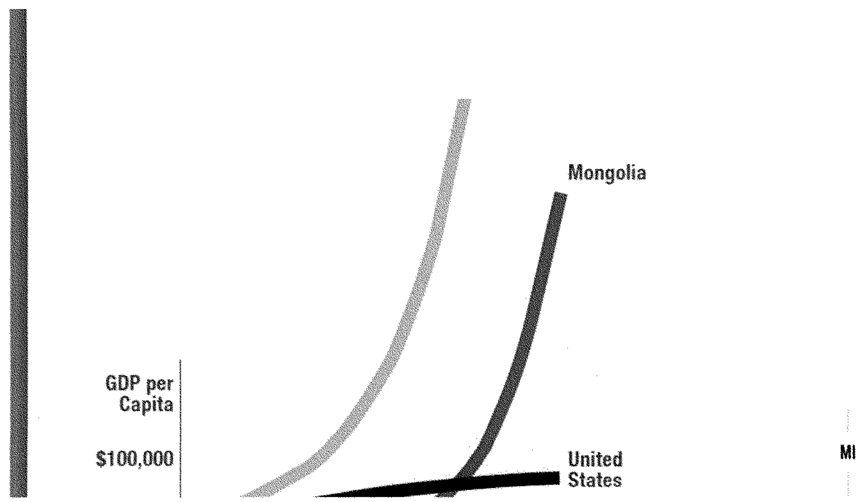
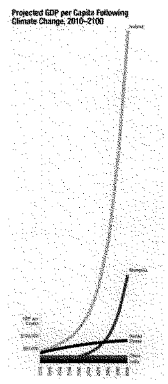

Mongolia
GDP per Capita
$100,000
United States
MI


Projected GDP per Capita Following Climate Change, 2010–2100
Iceland



Nature study of climate effect on growth

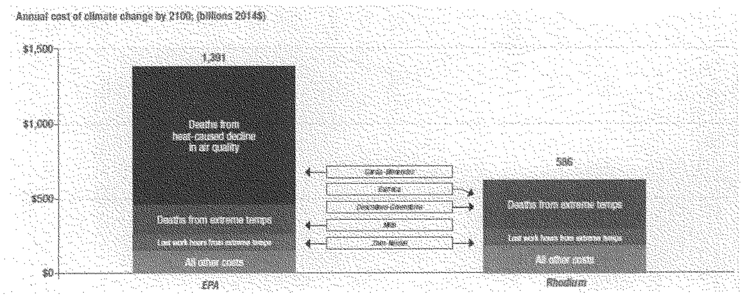
- Iceland and Finland become world's richest countries
- Canada's economy becomes seven times larger than China's
- India becomes the world's poorest country, shrinking at 4% per year

Why might this not be true?

- Assumes "other things constant" when other things are not constant
- Assumes the response to small, random changes will be proportionally comparable to the response to large, gradual changes

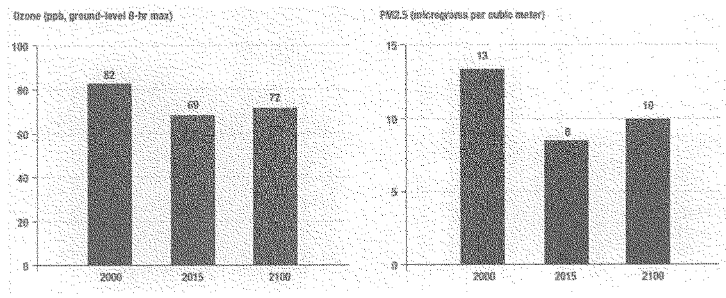
From Cass testimony before the House Committee on Science, Space, & Technology, Figure 5

GAO assessment of climate costs



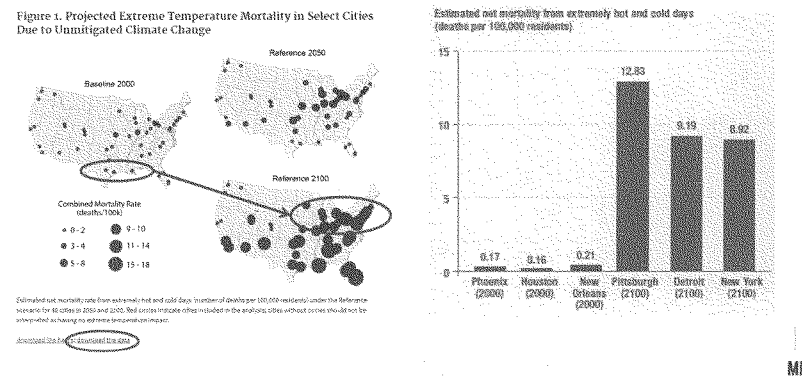
From Cass testimony before the House Committee on Science, Space, & Technology, Figure 1

EPA assessment of climate effect on air quality



From Cass testimony before the House Committee on Science, Space, & Technology, Figure 2

EPA assessment of climate effect on mortality



From Cass testimony before the House Committee on Science, Space, & Technology, Figure 3

Chairman SMITH. Thank you, Mr. Cass, very much.
Mr. Nordhaus.

TESTIMONY OF MR. TED NORDHAUS, EXECUTIVE DIRECTOR, THE BREAKTHROUGH INSTITUTE

Mr. NORDHAUS. Thank you for having me. It's an honor to testify today. My name is Ted Nordhaus, and I am the Founder and Executive Director of the Breakthrough Institute. We're an environment think tank located in Oakland, California. My think tank counts among its senior fellows a number of prominent climate scientists, technologists and social scientists, and my testimony today will draw upon this work to present a synthesis reflecting our assessment of the nature of climate risk, the uncertainties associated with action and inaction, and pragmatic steps that we might take today to address those risks.

To begin, let me offer a few observations about climate science and climate risk. First, there is a well-established scientific consensus regarding atmospheric anthropogenic climate change: global temperatures are rising, and that rise has been caused in significant part by greenhouse gas emissions resulting from the combustion of fossil fuels.

Second, and to the best of my knowledge, none of the witnesses called today for either the Majority or the Minority contest these well-established facts.

Third, there are a range of uncertainties beyond this consensus about the sensitivity of the climate, the likelihood of specific climate impacts, the capacity for adaptation, and the costs of mitigation that provide ample justification for either far-reaching and immediate action or no action whatsoever.

So how then should policymakers respond? Let me first address climate mitigation. Efforts to cap price and regulate greenhouse gas emissions have not much affected the trajectory of emissions anywhere to date. Under the best of circumstances, they have modestly tipped the scales toward lower carbon fuels and technologies. For this reason, the success of efforts to substantially drive decarbonization to levels that diverge from business-as-usual trajectories will depend primarily upon the availability of low-carbon technologies that are cheap and scalable.

Presently, there are important short-term steps that federal policymakers can take to assure that America sees continuing declines in emissions. Most importantly among these are measures to keep America's existing fleet of nuclear reactors online. We should also abandon misguided efforts to bail out the coal industry.

Reducing atmospheric concentrations of greenhouse gases to levels sufficient to much alter the trajectory of climate change, however, will require a concerted and collaborative effort between the public and private sectors to develop a range of low-cost, low-carbon technologies for the 70 percent of emissions in the United States that emanate from outside of the power sector in the industrial, transportation, and agricultural sectors. These include advanced nuclear energy, carbon capture, advanced renewable and geothermal energy, and long-term energy store capabilities.

Even in the best case, however, decarbonization efforts alone are unlikely to limit global temperatures to 2 degrees Celsius. For this reason, climate adaptation will play a large role in determining how well human societies weather a change in climate. Infrastructure, sea walls and flood channels, modern housing and transportation networks, water and sewage systems and similar are what makes us resilient to extreme climate events. As such, there are few things more impactful that this Congress could do than to substantially increase national investment in infrastructure so too recommitting ourselves to ensuring a comprehensive federal response to all natural disasters for all of America's citizens.

So to summarize, climate change is real, its origins are primarily anthropogenic, and it presents risks that are difficult to quantify but could be catastrophic. For this reason, reasonable measures to mitigate and adapt to climate change are prudent, but climate policy debates have too often overemphasized mitigation at the expense of adaptation focused on decarbonization at the expense of other mitigation pathways, attempting to make dirty energy expensive rather than clean energy cheap, and focused heavily upon renewable-energy technologies to the exclusion of the broad sweep of low-carbon technologies that will likely be necessary to deeply decarbonize the global economy.

So let me close finally with a call for moderation and humility on both sides of the aisle in place of bombast, alarmism, and denial in the face of irresolvable uncertainties that the issue presents America and the world will be better served by turning down the rhetoric and focusing on pragmatic measures to mitigate climate risk and adapt to risks that we won't be able to avoid.

Thank you very much for considering my testimony.

[The prepared statement of Mr. Nordhaus follows:]

Written Testimony of
Ted Nordhaus
Founder and Executive Director, The Breakthrough Institute

To the U.S. House of Representatives
Committee on Science, Space, and Technology

Hearing Entitled:
Using Technology to Address Climate Change

May 16, 2018

It is an honor to testify before this committee. My name is Ted Nordhaus. I am the founder and executive director of the Breakthrough Institute, an environmental think tank located in Oakland, California. I have spent a fair portion of my career working with environmental NGOs and have researched and written about the issue of anthropogenic climate change for most of the last two decades. My think tank counts among its senior fellows prominent climate scientists, technologists and social scientists whose work has been widely cited in the relevant scholarly literatures, the IPCC, and other leading assessments of the risks associated with anthropogenic climate change. My testimony today will draw upon this work to present a synthesis that broadly reflects our assessment of the nature of climate risk, the uncertainties associated with both action and inaction, and the pragmatic steps that we might take today to address those risks. All of the perspectives I offer today will be broadly consistent with the assessment reports of the Intergovernmental Panel on Climate Change.

Climate Science, Risk, and Uncertainty

Let me begin with a few observations about climate science and climate risk:

- First, there is a well established scientific consensus regarding anthropogenic climate change. That consensus is as follows - global temperatures, as measured at the surface level and the upper atmosphere have risen since the industrial revolution, that increase has been caused in significant part by anthropogenic forcings, notably the emissions of carbon dioxide from the burning of fossil fuels, and these anthropogenic greenhouse gas emissions are responsible for a significant share of anthropogenic forcing.[1,2] We also know that current CO2 concentrations in the atmosphere are higher than the Earth has experienced for at least several hundred thousand years, with most of the increase occurring since the early 1950's.

- Second, to the best of my knowledge, none of the witnesses called today, by either the majority or the minority, contest these well established facts.

- Third, while the basic relationship between rising atmospheric concentrations of greenhouse gases and global temperatures is well established, much else that might inform societal responses to climate change is not, including the extent of climate impacts that will result from rising global average temperatures, the costs to human societies of those impacts, and the cost of avoiding those impacts, where they can be avoided. To wit:

    - The IPCC estimates a wide range of temperature outcomes associated with a doubling of atmospheric greenhouse gas concentrations from pre-industrial levels. In the most recent IPCC estimate, published in 2014, the estimated range of climate sensitivity was 1.5 to

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[1] World Meteorological Organization, *WMO Statement on the State of the Global Climate in 2017* (2018), p. 4. https://library.wmo.int/opac/doc_num.php?explnum_id=4453

[2] Intergovernmental Panel on Climate Change. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2015). http://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

4.5 degrees celsius.[3] In the prior assessment, the range was 2 to 4.5 C.[4] In the next assessment, scheduled for 2022, that estimate will probably shift again.

- The estimated relationship between global temperature increases and climate impacts at the local and regional scales at which they actually affect human societies is also uncertain. While it is likely that many climate related phenomena will intensify, there is significant uncertainty as to by how much and over what timescales. This is true of most of the impacts that we worry most about, such as sea level rise, the intensity of landfalling hurricanes, the duration of droughts, or incidence of floods.

- We have limited foreknowledge as to how well human societies will adapt to climate impacts. This is due in part to uncertainties about the timescales and extent of climate impacts but arguably more so to uncertainties regarding the adaptability of human social, economic, and technological systems and the efficacy of the social and political institutions upon which they depend. Even a cursory review of the differential human and economic impacts associated with natural disasters of similar magnitude around the world should establish that the primary factor that mediates the relationship between natural disasters of various sorts and human impacts associated with those events are societal affluence, infrastructure, technology, and institutions.

- We have little certainty about the cost of climate mitigation. There have been many attempts to estimate the costs and benefits of mitigating climate change. But all are highly dependent upon assumed rates of technological change that are ultimately unknowable. Assume that technological change, with or without a helping hand from government, will be rapid, and the cost of deeply cutting greenhouse gas emissions will be very modest. Assume slower rates of technological change and costs will be prohibitive.[5]

• Fourth, given all of the uncertainties delineated above, one can find ample justification within the consensus climate science to advocate either far reaching and immediate action to mitigate climate change or no action whatsoever. Neither position is inconsistent with what we know with certainty about climate risk, as established by the IPCC and other similar assessments.

For all of these reasons, all discussions of climate change and what we ought to do about it revolve, unavoidably, around how we should orient ourselves toward uncertainty and risk. The dilemma that climate change ultimately presents us with is that we know that there is some significant possibility of catastrophic impacts *AND* that efforts to assess the appropriate response to those risks are confounded by cascading uncertainty and complexity in both the climate system and human social and technological

[3] Ibid., p. 43.
[4] Intergovernmental Panel on Climate Change. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (2008), p. 38. https://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_full_report.pdf
[5] See Edmonds, Jae, et al. "Technology and the economics of climate change policy." *Pew Center on Global Climate Change* (2000). https://www.c2es.org/site/assets/uploads/2000/09/technology_economics.pdf

systems. In my remaining remarks, I will offer some thoughts about how then we might best navigate those uncertainties in order to take wise action in the coming years and decades to both prepare for and mitigate climate variability and change.

Climate Mitigation and Uncertainty

Given high present day uncertainty, in which the consequences of inaction are potentially catastrophic and the costs of mitigation are potentially large, how should policymakers respond? Faced with many competing national and global priorities, what level of resources should we invest today to mitigate impacts that will unfold over the course of decades and centuries and whose consequences are highly uncertain and may not be knowable within the timeframes in which policy-makers have to act?

Let me first dispense with a common objection to asking the question in this way. Many suggest that we are already facing the consequences of anthropogenic climate change, in the form of increasingly severe climate related natural disasters. I will not attempt to parse for you the evidence for and against this claim. Rather I will simply observe two things that can be found in the consensus view of both the IPCC and the US National Climate Assessment.

- First, insofar as various studies have suggested that a climate signal can be found in recent disasters, the signal is relatively modest in the context of both known variability and projected future changes.[6,7] To take a prominent recent example, one recent study estimated that rainfall associated with Hurricane Harvey was 15% greater than would otherwise have been the case due to anthropogenic climate change. To put that finding in context, Hurricane Harvey produced an extreme rainfall event that resulted in approximately 40" of rainfall in some locations. The 15% increase associated with global warming according to this analysis would mean that Hurricane Harvey produced 40" of rainfall in these locations over three days rather than 34". I will let this committee draw its own conclusions as to whether 40" of rainfall rather than 34" of rainfall during this period materially contributed to the human and economic costs associated with this event. Suffice to say that the 34" of rainfall that the authors recognize was due to natural climate variability was an extreme event, outside of the observed climatic record for the region and would have brought extraordinary impacts without regard to additional anthropogenic forcings.[8]

- Second, even assuming that climate change is here today, intensifying natural disasters in some meaningful fashion, measures to mitigate emissions undertaken today will not appreciably influence the trajectory of either global temperatures or climate impacts for many decades to

[6] For example, this study suggests that warming will increase the area scorched by wildfires in Southern California: Jin, Yufang, et al.. "Identification of two distinct fire regimes in Southern California: implications for economic impact and future change." Environmental Research Letters 10, no. 9 (2015): 094005. http://iopscience.iop.org/article/10.1088/1748-9326/10/9/094005
[7] NASA. *The Impact of Climate Change on Natural Disasters.* https://earthobservatory.nasa.gov/Features/RisingCost/rising_cost5.php
[8] Geert Jan van Oldenborgh, et. al. "Attribution of extreme rainfall from Hurricane Harvey," Environmental Research Letters 12 no 12 (2018) 019501 http://iopscience.iop.org/article/10.1088/1748-9326/aa9ef2

> come.[9] To cite two prominent examples, when comparing low and high emissions scenarios produced by the IPCC, neither global average temperatures nor sea level rise see significant divergence for decades or perhaps until late in this century or early in the 22nd century.[10]

For these reasons, climate change has been a relatively low priority on the public agenda and is likely to remain so, despite longstanding efforts on the part of some to increase the salience of the issue. The asymmetry in timescales, between mitigation measures with present day costs and very long-term benefits is the reason that policies demanding high mitigation costs in the present to avoid unquantifiable risks far into the future have reliably failed politically, not only here in the United States[11] but almost everywhere else.[12,13] Explicit climate policies have not much affected the trajectory of emissions anywhere.[14,15] That fact has been obfuscated by both advocates of climate action, who have exaggerated the scope of the policies that have been proposed and initiated and opponents, who have exaggerated the cost of those policies.

To put a finer point on that observation, almost a decade after the US Senate failed to bring climate legislation to a vote, US carbon emissions today remain lower than the level that would have been mandated by the Waxman Markey legislation that passed this house in 2009.[16] The Waxman Markey proposal is not an isolated case. Similar efforts to cap emissions in Europe and California have established emissions caps that have proven with the benefit of hindsight to be consistently above the actual trajectory of observed emissions. For these reasons, it is difficult to take very seriously claims that these measures would have led to economic catastrophe, for the simple reason that they would have changed much less than either proponents or opponents claimed.

As such, policies to cap, price, or regulate greenhouse gas emissions, where they are established and well conceived, will likely very modestly tip the scales toward lower carbon fuels and technologies. The success or failure of efforts to substantially drive decarbonization to levels that diverge significantly from business as usual trajectories will depend primarily upon the availability of low carbon technologies that are cheap and scalable.[17] Reasonable pricing and regulatory strategies will have a role to play, but will be

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[9] Moss, Richard H., et al. "The next generation of scenarios for climate change research and assessment." *Nature* 463, no. 7282 (2010): fig 5b, pg 753. http://cmaps.cmappers.net/rid=1KJHRBBS9-X1Y02G-RJT/nature08823.pdf

[10] IPCC. *The Global Climate of the 21st Century*, 2001. https://www.ipcc.ch/ipccreports/tar/wg1/figspm-5.htm

[11] Center for Climate and Energy Solutions. *Congress Climate History*. https://www.c2es.org/content/congress-climate-history/

[12] Sengupta, Somini. *The New York Times*. "Why China Wants to Lead on Climate, but Clings to Coal (for Now)." Nov 14, 2017. https://www.nytimes.com/2017/11/14/climate/china-coal.html?

[13] Neslen, Arthur. *The Guardian*. "Secret UK push to weaken EU climate laws 'completely mad'", May 9, 2018. https://www.theguardian.com/environment/2018/may/09/secret-uk-push-to-weaken-eu-climate-laws-completely-mad

[14] van Renssen, Sonja. "The inconvenient truth of failed climate policies," *Nature Climate Change* 8 (2018), 355–358.

[15] Nordhaus, Ted and Jessica Lovering. *Breakthrough Institute*. "Does Climate Policy Matter?" Nov 28, 2016. http://thebreakthrough.org/issues/Climate-Policy/does-climate-policy-matter

[16] The Waxman-Markey legislation required a 3% emission cut from 2005 levels by 2012 and a 17% emission cut by 2020. This requires a 1.75% reduction per year from 2012 to 2016, so emissions should be at 10% below 2005 levels in 2016. As it happened, they were at an 11% cut from 2005. See https://grist.org/article/2009-06-03-waxman-markey-bill-breakdown/ and https://www.epa.gov/sites/production/files/2018-01/documents/2018_chapter_2_trends_in_greenhouse_gas_emissions.pdf

[17] International Energy Agency. *The Way Forward*, 2014. https://www.iea.org/publications/freepublications/publication/The_Way_forward.pdf

limited both by political limits to the short term costs that can be imposed in pursuit of uncertain climate benefits and the cost and availability of low carbon substitutes.

That should not, however, be the end of the story with regard to policy efforts to mitigate climate change. There is much beyond pricing or regulating emissions that policymakers can do to move us more rapidly in a cost-effective manner toward a lower carbon economy. Despite the industry's recent struggles, almost twenty percent of America's electricity still comes from nuclear energy,[18] a technology that was developed and commercialized through a range of federal policies and initiatives. America's world leading decline in emissions over the last decade has been achieved in large part due to the shale gas revolution,[19] which was made possible by decades of federal research, development, and demonstration efforts in partnership with the private sector.[20] Decades of policy support for wind and solar energy have begun to pay off as well, with costs falling rapidly and electricity penetration rising.[21]

There is much that federal policy makers can do to support continuing reductions in US emissions in the short term.

- This includes, most especially, keeping America's nuclear power plants open. Continuing plant closures threaten to undo much of the progress that America has made over the last decade due to both the transition from coal to gas and growing renewable energy shares. Whether through state and federal clean energy standards, intervention at the Federal Energy Regulatory Commission, or other measures, it is imperative that we keep America's zero carbon nuclear power plants operating.
- Natural gas, meanwhile, continues to displace coal-fired electricity generation.[22,23,24] Efforts to resuscitate the coal industry are misguided and doomed to fail due to the realities of energy economics. Coal is being displaced by a cleaner, cheaper, and more useful fuel due to market forces and we should let that transition run its course.[25]
- Finally, we should put claims that wind and solar energy are now economically competitive with fossil fuels to the test. I have long supported generous federal support for those technologies but it is clearly time to ramp those subsidies down and let existing wind and solar technologies stand on

[18] U.S. Energy Information Administration. *U.S. Nuclear Industry*, May 1, 2018. https://www.eia.gov/energyexplained/index.php?page=nuclear_use
[19] Middleton, Richard S., et al. "The shale gas revolution: Barriers, sustainability, and emerging opportunities." *Applied Energy* 199 (2017): 88-95. https://www.sciencedirect.com/science/article/pii/S0306261917304312
[20] Jenkins, Jesse, et al. *Breakthrough Institute*. "US Government History in Shale Gas Fracking History: An Overview." March 2, 2012. https://thebreakthrough.org/archive/shale_gas_fracking_history_and
[21] Cusick, Daniel. *Scientific American*. "Wind and Solar Growth Outpace Gas." Jan 12, 2017. https://www.scientificamerican.com/article/wind-and-solar-growth-outpace-gas/
[22] Nuccitelli, Daniel. *The Guardian*. "The war on coal is over. Coal lost." Oct 16, 2017. https://www.theguardian.com/environment/climate-consensus-97-per-cent/2017/oct/16/the-war-on-coal-is-over-coal-lost
[23] Goff, Michael. *Breakthrough Institute*. "How Natural Gas and Wind Decarbonize the Grid," July 13, 2017. https://thebreakthrough.org/index.php/issues/decarbonization/how-natural-gas-and-wind-decarbonize-the-grid
[24] Nordhaus, Ted, et al. *Breakthrough Institute*. "Natural Gas Overwhelmingly Replaces Coal," Dec 14, 2015. https://thebreakthrough.org/index.php/issues/natural-gas/natural-gas-overwhelmingly-replaces-coal
[25] McBride, Jameson. *Breakthrough Institute*. "Clean Energy Advocates Should Oppose Subsidizing Coal," Dec 7, 2017. https://thebreakthrough.org/index.php/voices/clean-energy-advocates-should-oppose-subsidizing-coal

their own so that they might survive the market test necessary to penetrate even further into the economy.

There will clearly be limits, however, to how far we are going to get with present low carbon technology. Even if wind and solar energy gets much cheaper, their variable nature means that without new and very low cost technologies capable of storing vast quantities of electricity for weeks and months, not days at a time, there will be both technical and economic limitations to how much electricity we can count on[26] from those sources. Nuclear energy still represents our largest source of zero carbon power,[27] but large conventional nuclear power plants are enormous public works projects that like many other similar endeavors have proven extremely costly to build.[28] Any nuclear renaissance worth speaking of in the United States will require a new generation of nuclear reactors that are much smaller and can be manufactured offsite. And because natural gas still has significant carbon intensity, the environmental benefits of the coal to gas transition are ultimately limited.[29] If natural gas is to fulfill its promise as a sustainable fossil fuel, we will need to develop and deploy at scale technologies of carbon capture and storage.

Moreover, roughly 70% of US carbon emissions arise from outside the power sector.[30] We have made some progress in the transportation sector, due to fuel efficiency and the commercialization of hybrid electric engines. We are just beginning to see the entry of electric vehicles into the light duty transportation market. But both hybrid and fully electric vehicles still require significant cost premiums and, for the latter, a huge build-out of charging infrastructure. As a result, it will likely be decades before we see the end of the internal combustion engine, if at all.

Outside of light duty transportation, the path to decarbonization is harder still. We have few viable low carbon substitutes for industrial heat and power, cement production, fertilizer, and heavy transportation. Carbon capture technologies could offer us a way to avoid emissions from fossil energy uses that we can't displace, but the path to economically viable carbon capture technologies for many applications is far from clear as well.

All of these new and improved technologies will require a significant and sustained commitment to mission-driven innovation in collaborative fashion between the public and private sectors to offer viable alternatives to fossil fuels in the United States and globally, and most are likely decades away from commercialization.

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[26] Beaudin, Marc, et al. "Energy storage for mitigating the variability of renewable electricity sources: An updated review." *Energy for sustainable development* 14, no. 4 (2010): 302-314.
[27] Center for Climate and Energy Solutions. *Climate Solutions: The Role of Nuclear Power*, April 2014. https://www.c2es.org/site/assets/uploads/2014/04/climate-solutions-role-nuclear-power.pdf
[28] Synapse Energy Economics. *Nuclear Power Plant Construction Costs*, July 2008. https://www.synapse-energy.com/sites/default/files/SynapsePaper.2008-07.0.Nuclear-Plant-Construction-Costs.A0022_0.pdf
[29] U.S. Energy Information Administration. How much carbon dioxide is produced when different fuels are burned? https://www.eia.gov/tools/faqs/faq.php?id=73&t=11
[30] EPA. *Sources of Greenhouse Gas Emissions.* https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

For this reason, the prospects for stabilizing atmospheric concentrations of greenhouse gases to levels consistent with limiting global warming to two degrees or less, the long-standing international target for climate stabilization, are extremely unlikely. Fossil fuels still constitute over 80% of primary energy consumption globally and in the United States and that share has hardly fallen since the oil shocks of the 1970's.[31] Most IPCC scenarios for stabilizing temperatures at 2 degrees celsius assume that the world removes enormous quantities of carbon from the atmosphere in the latter half of this century, something that we have no idea how to do at the scale that would be required.[32]

The likelihood, however, that in the next several decades atmospheric concentrations of greenhouse gases will rise to levels inconsistent with limiting global temperature increase to less than two degrees, should not be taken as reason to abandon mitigation efforts. The two degree target represents a political convention, not a particularly well established biophysical boundary.[33] There is no particularly strong empirical basis for the view that catastrophic climate impacts might be avoided should we succeed at stabilizing temperature below the two degree threshold nor that catastrophe is assured should we fail. Irrespective of the international two degree convention, the basic relationship between emissions and climate risk remains. Lower emissions bring lower long-term climate risk.[34] That includes both impacts whose relationships to global temperatures are relatively linear and climate tipping points that could bring non-linear impacts. Lower emissions bring lower risk of crossing tipping points that may or may not exist and whose precise location with regard to global temperatures is highly uncertain.

That basic relationship, between emissions and risk, is true today, when we have not yet surpassed two degrees of warming, and it will still be true several decades hence, when we have. All else being equal, cost-effective mitigation brings lower climate risk even recognizing that global mitigation efforts are highly unlikely to result in stabilization of atmospheric concentration of greenhouse gases at levels consistent with limiting the temperature increase to two degrees. Developing and deploying cost-effective technologies that reduce carbon emissions can also bring a range of further benefits, including improved public health from cleaner energy, lower energy costs, global competitiveness, and access to global export markets.

Adaptation for A Hotter World

Given the likely trajectory of emissions and global temperature, even presupposing much more far-reaching mitigation success than the global community has thus far made, climate adaptation will play a large role in determining how well human societies weather a changing climate over the coming decades and centuries. Adaptation in the context of anthropogenic climate change is, in most of its particulars, not much different than the steps that human societies reliably undertake as they modernize and develop. As societies become wealthier, their populations have become more resilient to climate

[31] The World Bank, *Fossil fuel energy consumption*, 2014. https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS
[32] Peters, Glen P., and Oliver Geden. "Catalysing a political shift from low to negative carbon." *Nature Climate Change* 7, no. 9 (2017): 619.
[33] Jaeger, Carlo C., and Julia Jaeger. "Three views of two degrees." *Regional Environmental Change* 11, no. 1 (2011): 15-26.
[34] Majkut, Joseph, *Reducing Emission, Reducing Climate Risk*, March 2016. https://niskanencenter.org/blog/reducing-emissions-reducing-climate-risks/

variability and extreme weather.[35,36] Modern, affluent societies are able to deploy infrastructure and technology to keep the weather at bay - sea walls and flood channels, modern housing and transportation networks, water and sewage systems, air conditioning to offer a few examples. Those measures are further amplified by modern institutions and practices - weather forecasts, emergency response systems, public health measures and the like.[37]

Citizens of wealthy economies are also much more mobile and integrated into national and global networks of trade and commerce that make them much less vulnerable to local and regional climatic disruptions. There has been a heavy focus among many concerned about climate adaptation upon increasing local resilience, mostly focused on localized food and energy production in the event that connections to regional and national networks are lost. And while there is clearly some utility in having backup power generation and water resources available in the immediate aftermath of a natural disaster, it is precisely our integration into global and national networks that make developed world populations so resilient to climate variability and disruption. The ability, for instance, to purchase food produced halfway across the country, or the world, in the midst of a drought, makes us much more resilient to that sort of climate variability, especially if it is sustained, as may become increasingly frequent.

Wealthy societies are able to abandon areas that become indefensible in the face of a changing climate and citizens of those societies are able to leave in search of better climates. Over the last fifty years, about 20% of the United States population has shifted from the northeast and midwest to the southeast and southwest, much of that due to voluntarily migration in search of better climates.[38] Those climates were not always so. Much of the southeast was historically malarial wetlands. Much of the southwest was inhospitable desert. Infrastructure and technologies have transformed those regions to desirable places to live. Climate change over the course of the next century may occasion migrations and transformations of similar scale. Good infrastructure and good institutions will greatly minimize the disruption and dislocation that could result from those shifts.

So the first critical thing to understand about climate adaptation is that we in the developed world are already very well adapted to climate change and, in many cases, also to the variability and change that we might experience in coming decades. The greatest risks to our continuing ability to be so will be our failure to invest in infrastructure and to tend to the institutions that we depend on to keep us safe. Hurricane Katrina was an extreme but otherwise ordinary hurricane that we should expect to see every so often along the Gulf Coast. But decades of neglected infrastructure exacerbated by neglect and incompetence on the part of state and federal emergency response officials turned it into a national tragedy.[39] We are watching a similar tragedy unfold in Puerto Rico today.

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[35] The World Bank, *Turn Down the Heat*, November 2012.
http://documents.worldbank.org/curated/en/865571468149107611/pdf/NonAsciiFileName0.pdf

[36] Fankhauser, Samuel, and Thomas KJ McDermott. "Understanding the adaptation deficit: why are poor countries more vulnerable to climate events than rich countries?" *Global Environmental Change* 27 (2014): 9-18.

[37] Noble, I.R., et al. "Adaptation needs and options." In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (2014) pp. 833-868.

[38] Frey, William, *U.S. growth rate hits new low as migration to the Sun Belt continues*, December 2016.
https://www.brookings.edu/blog/the-avenue/2016/12/23/u-s-growth-rate-hits-new-low-as-migration-to-the-sun-belt-continues

[39] Griffis, F. H. "Engineering failures exposed by Hurricane Katrina." *Technology in Society* 29, no. 2 (2007): 189-195.

Neither of these disasters can be laid at the feet of a rapidly changing climate. They are what we should expect in these regions and storms like those will, with certainty, occur again. Both disasters resulted from neglecting infrastructure, institutions, and the people who depend upon them. Even as it may continue to debate the merits of various climate mitigation measures, this Congress would substantially improve our long term prospects of adapting to climate change well if it agreed on a bipartisan basis to dramatically raise national investment in infrastructure and recommitted itself to ensuring a comprehensive federal response to all natural disasters for all of America's citizens.

What is true in the rich world is even more so in developing countries. Modern infrastructure is what makes us resilient to climate variability and natural disasters. The faster developing countries are able to build that infrastructure, the more resilient they will be to a changing climate. It is here that difficult tradeoffs between mitigation and adaptation are most problematic. Institutions can make a big difference and they can't really be disentangled from infrastructure. But the existence of hard infrastructure - steel and cement for housing, roads, hospitals, water and sewage systems - is the critical physical fact that makes societies more resilient to climatic extremes. Building that infrastructure is energy intensive and, as noted above, there are few viable low carbon alternatives presently available for many of the activities entailed in doing so.

This presents a quandary of sorts. Fossil fueled development globally increases climate risk. But it also makes developing world populations much more resilient to that risk. Infrastructure is an obvious example. But the basic dynamic is broadly applicable. Social and economic modernization is an energy intensive business and while there are some cases where that energy can be produced without carbon emissions, global development is, for at least the next several decades, almost certain to remain an enterprise that is primarily powered by fossil fuels.

There have been a number efforts through US funded global development institutions to establish sweeping restrictions on fossil fuel development, including at the World Bank, USAID, and the Overseas Private Development Corporation. While there may be some limited cases where this has been wise, trading off present day development for the poorest people in the world for uncertain climate mitigation benefits many decades hence is indefensible in my view. Development today makes poor populations much more resilient to both present day climate extremes and long term climate change. The United States should not stand in the way of poor nations around the world availing themselves of the same development and infrastructure that has made us so much more resilient to climate change, even if that development entails greater fossil fuel consumption.

Conclusion

In closing, I would like to suggest that America and the world would be better served by a bit more moderation in this body from both sides of the aisle. Climate change is real, its origins are primarily anthropogenic, and it presents real risks to human societies. Whether those risks will prove catastrophic, much less apocalyptic, simply cannot be foretold.

Lest anything I have said lead this committee to conclude that climate change does not constitute a significant threat to the American people, let me return to the question of uncertainty. An increasingly wealthy world faced with impacts that unfold gradually, over century timescales, should be able to adapt to them reasonably well. But there are unquantifiable risks of significant impacts that could unfold over decadal, not century timescales, and these are the sorts of impacts that even wealthy nations may not weather well. These risks, I will note, exist even if one is more inclined towards the low end of estimates of climate sensitivity. I am skeptical of calls to stabilize temperature at 1.5 degrees celsius and atmospheric concentrations of carbon at 350ppm.[40] But those demands are based in part upon studies of various climate impacts and tipping points that, while far from convincing in my view, cannot be dismissed out of hand either.

If the impacts associated with rising emissions unfold slowly and in linear fashion, then there is good reason to think that the United States and much of the rest of the world will manage those changes relatively well. The gradual migration of large populations from the Rust Belt to the Sun Belt took place over many decades and brought faster economic growth and improvements to overall well being. A large and sudden migration necessitated by rapidly unfolding climate impacts would not be so benign and would almost certainly bring very significant costs and disruption.

There are also important potential interactive effects between climate change and social and political institutions that should not be dismissed. I am skeptical of various claims that assert a causal link between civil strife in various parts of the world and climate change. But it is certainly plausible to suggest that worsening climate impacts in various parts of the nation and the world, in complex interactions with various other dynamics, might undermine the institutional capacities that allow us to establish and maintain resilience.

It is for this reason that continuing decarbonization efforts should remain an important priority, nationally and globally – with an urgent effort to push the cost and technical envelope for low carbon technology in order to hasten and reduce the costs of mitigation. It is also for this reason that we should explore other means to mitigate climate impacts beyond decarbonization, including carbon removal and geoengineering. Neither of these latter strategies represents an existing mitigation pathway today. But clearly, a reasonable assessment of the many uncertain futures that climate change could bring suggests that further research into these mitigation strategies is wise, not out of any certainty that they will be necessary but in recognition of the possibility that they might be needed.

The absence of much serious discussion among policy-makers regarding carbon removal and geo-engineering point to a broader challenge. Climate policy discussions have been overly dominated by a heavy focus on decarbonization and discussions of decarbonization have been further constrained by an overly narrow focus upon efforts to regulate or price emissions and promote renewable energy. Those measures will certainly have a role to play moving forward but mitigation efforts will need to take a range of other steps much more seriously, including the coal to gas transition, advanced nuclear energy,

[40] Nordhaus, Ted. *Foreign Affairs.* "The Truth About the Two-Degree Target," March 2018. https://www.foreignaffairs.com/articles/world/2018-03-07/truth-about-two-degree-target

advanced renewable energy technologies, carbon capture and removal, electrification, and geoengineering. Climate policy discussions will also be much better served to remember that adaptation to climate change is, in most cases, not appreciably different than the myriad measures we have already taken to make us more resilient to climate variability and extremes already. A broadening of the sorts of policies, technologies, and measures that we include in climate policy discussions might also bring the not inconsiderable benefit of substantially broadening the political coalition supporting climate action.

However we respond, climate change will under the best of circumstances be a chronic condition faced by human societies for many centuries to come. Accepting that reality, in non-apocalyptic terms, will allow us to mitigate, plan for, and adapt to that future most effectively and at the least cost to both present and future generations.

Thank you for considering my testimony.

Chairman SMITH. Thank you, Mr. Nordhaus.
And Dr. Duffy.

TESTIMONY OF DR. PHIL DUFFY, PRESIDENT AND EXECUTIVE DIRECTOR, WOODS HOLE RESEARCH CENTER

Dr. DUFFY. Thank you, Mr. Chairman, Ranking Member Johnson, and Members of the Committee for the opportunity to appear here today.

In my remarks this morning, I'm going to discuss the threat of global climate change but I do want to mention that I started my career in the Nuclear Weapons Complex at Lawrence Livermore National Laboratory, where I worked on nuclear-weapons testing and also on protecting the United States against the threat of nuclear ballistic missile attack.

The threat that I've devoted the bulk of my career to, global climate change, I believe to be equally important. In my remarks this morning, I'm going to focus on some of the science of climate change and on the role of technologies in addressing it, and on the leadership and business opportunities that I believe this presents.

The fact of global warming should be beyond question, so I won't review here the mountain of observational evidence we have documenting warming of the planet and associated related changes such as increases in some form of extreme weather, thawing permafrost, and so on.

The scientific consensus on human causation of climate change is as strong as the consensus on the fact of climate change itself, and I would like to quote from volume one of the fourth National Climate Assessment. This was released last November by the Trump Administration, and I quote: "This assessment concludes that it is extremely likely that human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century. There's no convincing alternative explanation."

Governments also recognize human causation of climate change. As of now, every country in the world is a party to the Paris Climate Agreement. It makes no sense to be part of that agreement if you do not recognize not only the seriousness of the climate threat but the human role in causing that threat.

Turning to technologies, we need technologies for mitigation of climate change, that is, preventing unacceptable climate change; for adaptation, that is, coping with unpreventable climate change; and we also need technology for measuring emissions of greenhouse gases. And my topline message this morning is that I hope our government will lead the development of these technologies not only because we need them but because once again this presents an opportunity for the U.S. research and business communities, and that's an opportunity that if we don't take advantage of, someone else will.

For mitigation, my first recommendation would be to accelerate deployment of the technologies we have now, namely wind and solar. We also do of course need new technologies for energy generation for energy storage and energy transmission. And because we've delayed so long in implementing effective climate policies, we now also need technologies to remove carbon dioxide from the atmosphere. And while we're developing those technologies, we do have an important opportunity to implement land management practices which can pull a significant quantity of carbon dioxide out of the atmosphere, and those same land management practices like reforestation and restoring wetlands and so on also have important benefits for climate adaptation.

Turning now to adaptation, we need a host of technologies for coping with the range of climate impacts. These include extreme weather, infectious disease, water contamination, water scarcity, food scarcity, and so on. The good news is that adaptation measures are generally cost-effective because in fact we're generally underadapted and underprepared for the climate we have today, and if you doubt that, you need look no farther than Houston or Puerto Rico.

Finally, I want to mention that we do need technologies to better measure greenhouse gas emissions. They say that you can't control what you can't measure, and any effective climate policy needs reliable techniques for measuring greenhouse gas emissions.

So in closing, I'd like to encourage you to support American efforts to do the research and to develop the technologies that we need to tackle climate change. Addressing this threat is an opportunity for American leadership that I would hate to see us miss.

Thank you for the opportunity to appear here this morning.

[The prepared statement of Dr. Duffy follows:]

THE BREAKTHROUGH

TED NORDHAUS
EXECUTIVE DIRECTOR

Ted Nordhaus is a leading global thinker on energy, environment, climate, human development, and politics. He is the co-founder and executive director of the Breakthrough Institute and a co-author of "An Ecomodernist Manifesto."

Over the last decade, he has helped lead a paradigm shift in climate, energy, and environmental policy. He was among the first to emphasize the imperative to "make clean energy cheap" in *The Harvard Law and Policy Review*, explained why efforts to establish legally binding international limits on greenhouse gas emissions would fail in the Washington Post and Democracy Journal, made the case for nuclear energy as a critical global warming solution in the Wall Street Journal, has written on the limits to energy efficiency and the need to prepare for climate change in the New York Times, and has argued for the importance of intensifying agricultural production in order to spare land for forests and biodiversity in Scientific American and the Guardian.

His 2007 book *Break Through*, co-authored with Michael Shellenberger, was called "prescient" by *Time* and "the best thing to happen to environmentalism since Rachel Carson's *Silent Spring*" by *Wired*. (An excerpt in *The New Republic* can be read here.) Their 2004 essay, "The Death of Environmentalism," was featured on the front page of the Sunday *New York Times*, sparked a national debate, and inspired a generation of young environmentalists.

Over the years, Nordhaus been profiled in the *New York Times*, *Wired*, the *San Francisco Chronicle*, the *National Review*, *The New Republic*, and on *NPR*. In 2007, he received the Green Book Award and *Time* magazine's 2008 "Heroes of the Environment" award.

Nordhaus is executive editor of the *Breakthrough Journal*, which *The New Republic* called "among the most complete efforts to provide a fresh answer" to the question of how to modernize liberal thought, and the *National Review* called "The most promising effort at self-criticism by our liberal cousins in a long time."

Testimony of Dr. Philip B. Duffy
U.S. House of Representatives Committee on Science, Space, and Technology
Hearing on "Using Technology to Address Climate Change"
May 16, 2018

Thank you Mr. Chairman, ranking member Johnson, and members of the committee for the opportunity to appear today.

I am Philip Duffy, President and Executive Director of the Woods Hole Research Center. I have a doctoral degree in applied physics from Stanford, and began my career in the nuclear weapons complex at Lawrence Livermore National Laboratory. There I worked in the group that tested nuclear weapons at the Nevada Test Site, and also on strategic defenses against ballistic missile attack.

The bulk of my career, however, has been devoted to a different and equally important threat, global climate change. For more than 20 years I studied climate change as a research scientist; I spent 3 years at a climate change communications organization, Climate Central (ending as their Chief Scientist); and between 2011 and 2015 worked on designing and implementing climate policies in the Obama White House.

Consensus on global warming and its human causation

Today I will discuss the need for technologies for mitigating (preventing) unacceptable climate change, for adapting to changes we can't prevent, and for monitoring greenhouse gas emissions. A top-line message is that development and deployment of these technologies present an important opportunity for US researchers and businesses. I will also mention the positive economic benefits that can be obtained from well-designed climate policies.

I'll start, however, by reviewing some of what we know about climate change and its human causation.

The fact of global warming is beyond question. An enormous quantity of observational evidence clearly demonstrates warming of the atmosphere and ocean, melting of land and sea ice, sea level rise, reductions in snow cover, and a host of other consequences of warming, such as increases in extreme precipitation and other forms of extreme weather.

The scientific consensus on human causation of observed warming is as strong as on the fact of warming itself. The latest scientific estimate presented by the Intergovernmental Panel on Climate Change (IPCC) is that humans are responsible for essentially all of the warming observed over the past 60 or so years. This is supported by the latest US National Climate Assessment, the first volume of which was released by the Trump administration in November 2017. This Assessment found that "...based on extensive evidence, ... it is extremely likely that **human activities, especially emissions of greenhouse gases, are the dominant cause of the observed warming since the mid-20th century**. For the warming over the last century, there is no convincing alternative explanation supported by the extent of the observational evidence."

It is important to note that world governments also share the consensus on human causation of climate change. IPCC summary statements, including those on attribution of warming to human activities, are not only produced and reviewed by hundreds of scientists from nations around the world, they are approved by governments as well. In fact, every sentence in the IPCC summary documents, again including those on human causation of climate change[1], were approved *unanimously* by national representatives. Furthermore, every country in the world has signed onto the Paris climate agreement, which commits them to taking steps to reduce their contributions to climate change. There would be no reason to do that if they did not recognize both the importance of the climate threat and the human role in causing it.

Let me add that any alternative explanation for recent climate change (other than human greenhouse gas emissions) faces two challenges: first, it must provide an alternative physical mechanism for observed warming, and second, it must explain why the observed increase in atmospheric greenhouse gases is *not* responsible for observed warming. This would require overturning the scientific understanding of the greenhouse effect, that has been developed over the course of nearly two centuries and that, in its current form, explains observational data with striking fidelity.

Finally on this subject, while we understand more than enough about climate science to know that we need to urgently implement strong climate policies, there are important policy-relevant issues that need to be better understood. Chief among these may be "tipping points," climate processes which would be impossible to stop after they have been set in motion, and which would have severe societal consequences. These are discussed further below. I encourage this Congress to support increased funding for research into these questions and others that the Congress may feel need to be better understood. In particular, if despite the overwhelming evidence supporting human causation of climate change, the Congress feels that the human role in climate change needs to be better understood and debated, then I encourage them to support increased research funding, in order to ensure that that debate is as well-informed as possible.

Tipping points and the urgency of addressing climate change

The oft-cited urgency of addressing climate change has a strong basis in science. Part of this basis is the long lifetime of CO2 in the atmosphere. This implies that even if human greenhouse gas emissions were to instantly and completely cease, the elevated global temperature and its many climatic and human consequences would not materially improve for centuries. Sea level would continue to rise for a thousand years. The policy ramifications of this are fundamental: "wait and see" is a bad climate policy, because if the effects of climate change become intolerable it will be too late to avoid being forced to cope with them for centuries, if not longer.

The urgency of addressing climate change is also driven by thresholds and tipping points such as the onset of large-scale emissions of greenhouse gases from thawing permafrost. The disintegration of major land ice sheets is another process which may become irreversible and which would produce devastating global consequences—massive sea level rise. Improved scientific understanding of these processes, and observations showing them starting to occur, are the main reasons why policy discussion increasingly focus on the stricter goal of limiting global

[1] The most recent such statement is: "It is *extremely likely* that human influence has been the

warming to 1.5°C rather than the older 2° goal. As noted above, we urgently need more research in order to understand as precisely as possible where these tipping points lie, to allow us to refine our top-line climate policy goals (e.g. should we limit warming to 1.5°, 2°, or something else?) in order to be sure to avoid the consequences of crossing these thresholds and tipping points.

The urgency of addressing climate change is also driven by societal factors. For example, well before coastal areas are permanently or even usually inundated, property values in these areas may drop. Inability to get affordable insurance, or any insurance at all, may accelerate this decline. We urgently need policies to delay or prevent inundation and flooding, as well scientifically and economically sound policies on insurance, disaster response, rebuilding, and so on.

The need for technologies

Technology will play an essential role in minimizing the effects of climate change and adapting to the effects we cannot prevent, as well as in measuring greenhouse gas emissions. I would like to see our government help US businesses to develop these technologies and sell them to the rest of the world. If we don't, someone else will, and I would hate for our country to lose that opportunity.

To begin with reducing emissions, both developed and developing countries want, deserve and will seek the best possible quality of life for their people. This means an increase in global energy use. It is very much in our own self-interest to help other countries to accomplish this with technologies that do not contribute to climate change. Otherwise, the greenhouse gas emissions from these countries will result in climate consequences that will be extremely harmful to all nations, including us. Key technologies needed for mitigation include those for carbon-free energy generation, storage, and transmission, as well as for climate-friendly agriculture and forest management. In addition, we need technologies for energy efficiency, for electrification of the transportation and industrial sectors, and so on. Finally, I believe that we should at least investigate technologies for counteracting the effects of atmospheric greenhouses gases, a practice known as geoengineering.

Because we have delayed so long at implementing effective emissions reductions measures, we also need technologies to remove CO2 from the atmosphere. Although it may in the future be possible to achieve this using technological means, it is possible now to achieve significant CO2 removal using land management practices like reforestation and climate-smart agriculture. I recommend adoption of these practices as they have significant positive side-benefits, including making us more resilient to climate threats.

An enormous range of technologies is needed for climate adaptation. These include technologies to cope with extreme weather, water contamination, vector borne diseases, to increase resilience of crops, and so on. With respect to extreme weather, assessments have shown that we are under-prepared even for the present climate, meaning that investments in preparedness and resilience would produce net economic savings even absent human-caused climate change. Upgrading our physical infrastructure could be an important step in increasing resilience, if that infrastructure is designed with the climate of the 21st century in mind.

New technologies are also needed to measure greenhouse gas emissions. Any policy to meaningfully control climate change will require the ability to accurately and verifiably measure these emissions. Needed technologies include those for measuring carbon in the atmosphere, ocean, forest, soils, etc. both remotely and *in situ*, as well as advanced modeling to understand where emissions are coming from. Here again, I would hope that our government would help the United States to be the leader in the development and deployment of such technologies. The recent decision to cancel NASA's Carbon Monitoring System is ill-advised as the information gathered by such systems will generate real value at low cost.

Climate policies and their economic consequences

Mitigation and adaptation are sometimes presented as alternatives, but this is a false dichotomy. Focusing exclusively on mitigation would leave us needlessly vulnerable to harms from unavoided climate change. Ignoring mitigation would expose us to potentially catastrophic consequences. We are already practicing both mitigation and adaptation, and this will continue to be true. As noted above, investments in adaptation often save more money than they cost.

Results of early studies suggest that the same is true of mitigation policies. We are beginning to have enough real-world experience with these policies that we can learn valuable lessons by studying not only their effectiveness at reducing greenhouse gas emissions but also their immediate economic impacts. Forty countries and 20 subnational jurisdictions are now under a carbon pricing policy (carbon tax or emissions trading system). Assessments of these policies have found that well designed climate policies can not only reduce greenhouse gas emissions but have immediate positive economic impacts. Several recent studies, for example, found that the Regional Greenhouse Gas Initiative (RGGI), a "cap and trade system" on greenhouse gas emissions from the electric power sector in nine northeastern states, has resulted in billions of dollars of net economic benefit to the region[2], as well as $5.7B in savings due to improved health outcomes[3]. While these studies are limited in scope, the idea that the same policies that address climate change can also improve the economy is powerful and important.

Conclusion

The threat of global climate change is real and urgent, and is recognized as such by scientists and governments around the world. Advanced technologies of many types will be essential in minimizing and adapting to this threat.

I recommend specifically:

• Accelerated deployment of carbon-free energy production technologies we have now, especially wind and solar;

• Development of new such technologies, as well as technologies for energy storage and transmission;

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[2] https://www.dec.ny.gov/docs/administration_pdf/ag11rggi.pdf

www.analysisgroup.com/uploadedfiles/.../analysis_group_rggi_report_july_2015.pdf

www.analysisgroup.com/uploadedfiles/.../analysis_group_rggi_report_april_2018.pdf

[3] http://abtassociates.com/RGGI

- Development of technologies to remove CO_2 from the atmosphere;

- Research into geoengineering;

- Adoption of land-management practices that remove CO_2 from the atmosphere;

- Development of improved technologies for measuring GHG emissions and global carbon stocks

- Accelerated research into understanding climate thresholds and tipping points, in order to inform top-line climate police goals (e.g. 2° vs 1.5°);

No nation is better position than ours to develop these technologies and to profit economically from their deployment. I enthusiastically encourage this Congress to support and enable US leadership in this area.

Philip B. Duffy is President and Executive Director of the Woods Hole Research Center (WHRC). Dr. Duffy was trained in physics and started his career in the nuclear weapons complex at Lawrence Livermore National Laboratory. There he was involved with testing nuclear weapons at the Nevada Test Site, and also worked on strategic defenses against nuclear ballistic missile attack. Turning to the threat of global climate change, Dr. Duffy studied the problem for 20 years as a research scientist. Between 2011 and 2015 he helped to formulate and implement domestic and international climate policy in the Obama White House. Prior to joining the White House he was Chief Scientist at Climate Central, a non-profit dedicated to increasing public understanding and awareness of climate change. He has been a Senior Scientist at Lawrence Livermore National Laboratory, an adjunct faculty member at UC Merced, and has held visiting academic posts at Stanford University and at the Carnegie Institution for Science. Dr. Duffy has over 75 peer reviewed publications, has served on committees of the National Academy of Sciences, and as an advisor to the US Department of State. He has a bachelor's degree from Harvard and a PhD from Stanford University.

Chairman SMITH. Thank you, Dr. Duffy, and I'll recognize myself for questions.

And Mr. Cass, let me direct my first one to you. You put up a couple of slides today. One had to do with the number of heat deaths increasing exponentially, particularly in the Northeast. Would you go into just some quick detail as to why that study was flawed? And you mentioned the Rhodium study as well, but take your pick. Just why are some of these studies flawed and why should we sort of discount them?

Mr. CASS. Sure. Thank you. I think to understand conceptually why they're flawed, it's important to recognize that all regions, even within the United States, adapt to their local climate, and so when you look across the country you find, for instance, that people in the hotter parts of the country are not suffering from higher heat-related mortality than people in the cooler parts. The logical conclusion to draw from that would be that as the country gets warmer, we should not expect to see a lot more heat-related deaths because, again, people will adapt to whatever heat they face, and indeed, that's what the most recent published literature shows.

What studies do instead to generate large heat death estimates is to look at the reaction we have seen historically even per hot day or per days that are especially hot for a location and simply extrapolate forward if we see many more hot days than surely we will see that many more deaths. And the EPA study is the best example of this where they take a city like Pittsburgh and they say if one percent of Pittsburgh days have lows above 71 degrees, we will call that extreme heat for Pittsburgh, and whatever the death rate they experience on those days they will continue to experience that death rate on days when the temperature is above a low of 71 even if that becomes very common in the future and so you see the death rate in Pittsburgh skyrocket if you assume that. Of course, if the climate in Pittsburgh shifts to be more like that of a more southerly city, Pittsburgh's use of air conditioning and other adaptive technologies will shift as well, and the result will likely be that we will see the same low death rate that we do today.

Chairman SMITH. Okay. Thank you, Mr. Cass.

Mr. Nordhaus, I appreciate your good point that given the uncertainties we all could use some moderation and humility. A good reminder.

What I wanted to ask you about is, you mentioned that we couldn't just rely upon renewable energy; we need to make better use of fossil fuels. Would you go into some detail or give examples of what you're talking about?

Mr. NORDHAUS. Well, I think the primary point that I would want to stress to this Committee, a couple of things. The first is that whatever we may think we should do, the evidence is pretty strong that 70 percent of U.S. energy, well over 70 percent of U.S. primary energy still comes from fossil fuels. That's true globally. And despite longstanding efforts, that has not changed very much going all the way back to the oil shocks of the 1970s. So part of that we could do better. Part of that, there are a lot of uses of fossil fuels that we don't have very good alternatives for. We spend a lot of time arguing and talking about various technological pathways in the power sector, which is a little bit like looking for your keys under the light post because that's where the light is. That's the easy place where there really are good options for decarbonization so we like to argue about that, but once you get outside of the power sector into industry, heavy transportation, and agriculture, it gets much harder.

Secondly, in the developed world, there are very significant tradeoffs. The things that make us resilient to climate extremes, whether they are caused by climate change or just normal climate variability, are infrastructure, and infrastructure, building infrastructure, is a really energy-intensive business—steel, cement, things like that, and again, those are exactly the sectors we don't have particularly good alternatives, low-carbon alternatives in. So for that reason, I think there's important tradeoffs, especially when we think about poor countries and their use of fossil fuels, that we need to keep in mind in terms of what will make those countries in the coming decades most resilient to a changing climate.

Chairman SMITH. All right. Thank you, Mr. Nordhaus.

And Dr. Duffy, I appreciated your mention of technology. Obviously I agree with that. You mentioned your background and your experience, let's call it with nuclear energy, at least that's the way you started at Lawrence Livermore, and I'm wondering if you feel that if we do develop nuclear fusion as many expect to in the next ten years, I mean, there's almost nothing else we could do that would have more of a dramatic impact on reducing carbon emissions, I think, than nuclear fusion. Do you agree with that, or what impact do you think that would have if we came up with a cost-effective way of producing that kind of energy?

Dr. DUFFY. Well, Mr. Chair, thank you for the question. I just want to clarify. My experience at Lawrence Livermore National Lab was with nuclear weapons.

Chairman SMITH. I knew that. I was actually——

Dr. DUFFY. And——

Chairman SMITH. It's still nuclear. I was hoping——

Dr. DUFFY. I'm proud to be a tree hugger but I don't think there's too many tree huggers who've detonated nuclear bombs.

Chairman SMITH. Okay.

Dr. DUFFY. As far as nuclear fusion goes, I mean, it's been 30 years in the future for at least 30 years.

Chairman SMITH. Okay.

Dr. DUFFY. I will say I do support Mr. Nordhaus's opinion that we need to make better use and more extensive use of nuclear fusion.

Chairman SMITH. Okay. Thank you, Dr. Duffy.

I'm going to do something that I don't do very often, and that is, without objection yield myself an additional minute, and the reason I'd like to do so is because Dr. Curry is not here but I would like to put up a slide that I was going to use had she been here, and I'd like all Members to take a look at this.

[Slide]You will see that for the last 100 years, sea-level rise has been basically constant. It's been going up at about 1.8 millimeters per year, and you'll see that there appears to be no correlation between the increase in the sea level and carbon emissions, and I just want to put that up there for our edification. I was going to ask Dr. Curry about it but I think it kind of speaks for itself.

Dr. DUFFY. I'd like to comment on that, Mr. Chair. You know, you've shown a sea-level record from one location.

Chairman SMITH. Right. This is San Francisco. It's also Boston, which appears to be——

Dr. DUFFY. The rate of global sea-level rise has accelerated and is now four times faster than it was 100 years ago.

Chairman SMITH. Is this chart inaccurate then?

Dr. DUFFY. It's accurate but it doesn't represent what's happening globally. It represents what's happening in San Francisco.

Chairman SMITH. All the charts I've seen, whether it be San Francisco, whether it be Boston or anywhere else show about the same degree of increase. I'm welcome to look at whatever you want to propose but this is——

Dr. DUFFY. I'd be happy to show that to you.

Chairman SMITH. These are objective charts that I've seen, so thank you, Dr. Duffy.

That concludes my questions, and the Ranking Member, Ms. Johnson, is recognized for hers.

Ms. JOHNSON. Thank you very much, Mr. Chairman.

Our understanding of Earth's climate system continues to improve, and within some of our lifetimes, we've seen the accuracy of our short-term weather forecasts improve dramatically. As a matter of fact, just the time that I've been in Congress, we've seen improvement in travel. Yesterday, for example, it took me about seven hours to get here from Dallas, Texas, because of weather. We didn't see the weather but it was predicted, and we made it and we got here.

So Dr. Duffy, how do you respond to those who suggest that we cannot adequately anticipate the consequences of climate change in order to develop effective mitigation and adaptation strategies?

Dr. DUFFY. Thank you for the question, Ranking Member Johnson. I would say this. You know, the climate models that we have do faithfully reproduce the broader outlines of physical climate change, and these include increases in the global temperature, polar amplification, that is, more rapid warming, particularly in the North Pole, increases in precipitation and extreme precipitation, although those are actually underpredicted by climate models. The models also predict loss of sea ice, although again they've underpredicted the observed rate of loss of sea ice, and similarly, the models predict loss of land ice but once again have underpredicted the rate that that's occurred. The models predict stratospheric cooling, thawing permafrost, increases in heat exchange. All of these phenomena have been very accurately representative models.

And I'm glad that you actually mentioned the miracle of weather prediction because there is a connection between making climate projections and the miracle of weather prediction and actually some of the European centers that do a very, very good job at day-to-day weather forecasting use literally the same computer program for their climate predictions that they use to predict day-to-day weather, and again, those are literally the best weather forecasts in the world today.

Ms. JOHNSON. Thank you very much.

If we veer away from looking into climate change and its effects and look in another direction or deny it's there at all, I think we'll fail to improve our predictions, and where do you think that will take us? Because if we can stop—we can stop anything we want to here but it doesn't stop climate change. We can deny it happens but it does happen. And so if we look the other way and decide that we are not going to research, what do you think the outcome might be?

Dr. DUFFY. Well, thank you for the question. You know, the outcomes from unmitigated climate change are not pretty, and I'm very happy to hear both of my co-witnesses supporting the need for both mitigation and adaptation. You know, one of the things that I'm most concerned about with climate change is the threat of crossing so-called thresholds and tipping points, and what that means essentially is processes which once underway become irreversible, and one of those is the thawing of permafrost, which I mentioned. Permafrost is mostly in the Arctic. It sounds far away but there's an enormous quantity of carbon tied up in frozen permafrost. It's starting to thaw. It's starting to release greenhouse gases. That threatens to become an unstoppable process, which would greatly amplify global warming.

And I'll just mention one more, and that is the decay of the major land ice sheets. Similarly, those processes are probably slow but we may be very near the point where they become unstoppable and therefore commit the planet to many, many meters of sea-level rise.

Ms. JOHNSON. Thank you very much.

Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Ms. Johnson.

Without objection, I'd like to put in the record, this is an op-ed in today's Wall Street Journal by Fred Singer. He is a Professor Emeritus of Environmental Science at the University of Virginia, and he founded the Science and Environmental Policy Project. The headline on this op-ed is "The sea is rising but not because of climate change."

[The information appears in Appendix II]

Chairman SMITH. We'll now go to the gentleman from California, Mr. Rohrabacher, for his questions.

Mr. ROHRABACHER. Well, thank you very much. Let me just note before I ask any questions, I have in my career been very supportive of trying to develop certain technologies that I consider to be more efficient at providing the energy needs for the people of the world, whether it's nuclear energy, which we're talking about now, and by the way I would hope, Mr. Chairman, that we don't focus on the development of nuclear energy that is least likely to be developed. We can actually do fission reactors now that are very efficient and come to play in this issue as compared to fusion, which it seems always to be 20 years away, 30 years away, and always will be. We can produce safe nuclear reactors right now if we'd focus on fission and quit wasting our money on fusion, but that's a disagreement. Thank you.

But also, you know, I believe in solar and wind and all the rest of these as long as they pencil out and what we need is a new battery technology, which I understand is on the way, when those things will actually become profitable and people will naturally go in that direction because, correct me if I'm wrong, doesn't the amount of carbon that is put in the air reflect the fact that we are not efficiently producing energy? Isn't that what we're talking about here? I believe so. But when you come down to this debate over adaptation versus mitigation, there's an insistence when people talk about mitigation that we control human behavior rather than having people naturally evolve in response to that need, and so I'm a little bit disturbed by, number one, that over and over again I hear don't ever talk about whether or not mankind is the main cause of the temperature changing and the climate changing. That's a little disturbing to hear constantly beaten into our heads in a Science Committee meeting when basically we should all be open to different points of view.

Because the answer that we've been given in terms of mitigation versus adaptation is that we need controls over people's lives and make their decisions for them rather than adapt economically and elsewise. Let me ask you whether or not any of you on the panel would agree that solutions—I've read a number of studies that have indicated there's certain solutions that are being advocated. One study is that we should be eliminating pets, dogs. Dogs should be eliminated, and that's part of their solution that we're going to do that. There was one that talked about ending frequent-flier miles, and others who talk about how we need to have major increase in parking fees and gas taxes. Now, do any of you on the panel agree that that approach—no more dogs, you can't have a dog as your pet, we're going to outlaw those things, no more frequent-flier miles, and by the way, ordinary people benefit from frequent-flier miles and dogs, and now you have to see them on the airplanes actually—versus major increases in parking fees? Do any of you support that type of human control in order to come to grips with what you're telling us is absolutely undebatable, that man caused global warming? Do any of you agree with any one of those solutions? Go ahead.

Mr. NORDHAUS. No.

Mr. ROHRABACHER. Okay.

Mr. NORDHAUS. I will say that, as I indicated in my written testimony, I think that modest tax, regulatory pricing policies can help modestly move us at a cost-effective way towards lower carbon technologies but the underlying sort of fundamental facts that will determine how far we get will be the availability of low-cost, low-carbon technologies, and that's going to require a lot of continuing innovation.

Mr. ROHRABACHER. And like as they say, the amount of carbon going into the air reflects that that technology is not as efficient as other means. Now, those of us who don't believe that we should be expanding the control of the government over our lives and that people should actually have more decisions rather than less, that's the area of contention that I see here.

Mr. Chairman, thanks very much for this hearing.

Chairman SMITH. Thank you, Mr. Rohrabacher.

And the gentlewoman from Oregon, Ms. Bonamici, is recognized.

Ms. BONAMICI. Thank you very much, Chairman, and thank you again to our witnesses.

Dr. Duffy, you mentioned when you were talking about clean, renewable energy sources, you mentioned wind and solar. In Oregon off our coast, we're doing some great research on wave energy and harnessing the power of the oceans. There's so much potential there. Our economy in the Northwest is really dependent on the health of the ocean and the lower Columbia River estuary, and people fish in our rivers and lakes and oceans and hike in our forests. We rely on those natural resources to support a significant portion of our economy, and many of those are vulnerable to the effects of climate change, and my constituents are already experiencing some challenges. We have wineries and farmers who are very concerned about drought as temperatures continue to rise. Our coastal communities are worried about the vitality of the commercial fishing and shellfish industries as high levels of carbon dioxide in the atmosphere are changing ocean chemistry, and I know they're working hard on adaptation but they're also very concerned about why the ocean conditions are changing and how they're changing.

We've had higher than usual spring and summer temperatures and earlier snowmelt, changing the dynamics of the tourism industry, and we understand that climate change can have significant effects on the economic stability of a region or a nation.

So would you talk a little bit about how this economic growth could be stalled as a result of these challenges but also importantly, what is the cost of inaction? My colleague was just pointing out that renewables make sense when they pencil out but what are the costs of not taking action?

Dr. DUFFY. Well, thanks so much for the question. I mean, you just mentioned—I mean, you just partially answered your own question. You listed a number of local impacts of climate change that are happening now, are affecting folks in your district. I also come from a coastal region. We have actually very, very similar concerns. A big part of our local and regional economy is based on fishing. We have serious problems with rapid ocean warming, with sea-level rise and so on.

You know, you asked, you know, what are the economic concerns. I mean, there's a range including consequences of extreme weather impacts on food scarcity, impacts on water scarcity and on and on.

Ms. BONAMICI. Thank you. You know, we've had a lot of conversations in this Committee about the cost of regulation, especially with things like the Clean Power Plan, and should there be a regulation, should the market or technology solve the problem. Does not regulation drive the development of technology? If there is a regulation, does not that encourage the private sector and researchers to develop the technologies that we need to comply with regulations, Dr. Duffy?

Dr. DUFFY. You know, that's a great question, and you know, as I think you know, I worked for years in California, and there was a fascinating study done of the effect of regulation of both energy efficiency and refrigerants on the cost of refrigerators, and what it showed is that the cost of refrigerators historically went up, up, up, up, up until the onset of regulation at which point the cost of refrigerators went down, down, down, down, down as the size of the refrigerators and their energy use—well, the energy use went down, the size continued to increase. So yes, actually regulation can be a stimulant for technological innovation.

Ms. BONAMICI. I also wanted to mention, we had a lot of wildfires in Oregon last year. We had unusually hot and dry conditions, and of course, the fires and smoke created dangerous conditions for all populations but especially with, you know, women, seniors, children, people living with chronic health conditions, and even residents living miles away found ash throughout their neighborhoods. So could you discuss the difference between committing resources to understanding the connection between climate change and extreme weather events and simply adapting to those events as we experience them?

Dr. DUFFY. Thanks for the question, and you know, you mentioned wildfires specifically. There have been huge increases, a sixfold increase in area burned by wildfire in the western United States in the last 30 years. Some of that is due to changes in forest management practices. I saw a study recently that attributed roughly half of the increase in area burned to human-caused climate change. It's not hard to understand why that would be. The fire season is longer. Temperatures are hotter. By the end of the fire season, we have a lot of fuel that's getting awfully, awfully crispy, and we have had record number of fires and record amounts of area burned.

Ms. BONAMICI. Right, and my time is expired. I yield back. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Ms. Bonamici.

And the gentleman from Alabama, Mr. Brooks, is recognized for his questions.

Mr. BROOKS. Thank you, Mr. Chairman.

Ever since human beings have been on the planet, sea levels have risen relative to ground levels. Why is that? Any of you can opine as you wish.

Dr. DUFFY. Well, I'd be happy to address that. Sea levels over the last three million years have gone up and down in line with the cycles of ice ages and interglacials, and I can expound on the science if you wish. The recent, the last 100-year increase in sea-level rise, as I mentioned earlier, has clearly been attributed to human activities. Greenhouse gas emissions——

Mr. BROOKS. That wasn't the question. I appreciate your wanting to expound on that. My statement is that since human beings have been on Earth, sea levels have risen. What are the factors that have caused it to rise?

Dr. DUFFY. Well, as I said, sea levels have gone up and down——

Mr. BROOKS. I'm talking net, not fluctuations.

Let's assume that for a moment that what you're talking about has some kind of factual, rational basis for it that ice has melted. Are there other factors?

Dr. DUFFY. No, look, you know——

Mr. BROOKS. No, there are not other factors, Mr. Duffy?

Dr. DUFFY. Looking at the history of sea-level rise is very informative, and one of the things that we see, for example, is that the last time the global temperature was as high as it is——

Mr. BROOKS. Dr. Duffy, you're not answering my question again. I'm conceding for the moment that there has been ice meltage compared to what it was three million years ago, whatever, since that's the timeframe you used. I'm asking another question, and that is, what other factors have caused the sea levels to rise relative to dry land? Does anyone else have any—I mean——

Dr. DUFFY. Okay.

Mr. BROOKS. —in particular, Dr. Duffy, you said they're going to be massive. Isn't that the word that you use in your remarks, massive sea-level rises? Don't you think if you're going to make that kind of statement you ought to have some idea as to what all the causes of sea-level rises have been?

Dr. DUFFY. Sure, and if you're referring to ground subsidence, that is a factor in some regions.

Mr. BROOKS. Okay. What else? That's one. So now we've gotten two. What else?

Dr. DUFFY. Ground subsidence is not going to cause the levels of sea-level rise that arouse my concern.

Mr. BROOKS. I'm just asking for factors. I was not asking for your prioritizing of one over the other but you mentioned two. What else?

Dr. DUFFY. Those are all that I know of.

Mr. BROOKS. What about erosion? Every single year that we're on Earth, you have huge tons of silt deposited by the Mississippi River, by the Amazon River, by the Nile, by every major river system, and for that matter, creek all the way down to the smallest systems, and every time you have that soil or rock, whatever it is that is deposited into the seas, that forces the sea levels to rise because now you've got less space in those oceans because the bottom is moving up. What about——

Dr. DUFFY. I'm pretty sure that that's——

Mr. BROOKS. —the white cliffs of Dover, California where you have the waves crashing against the shorelines and time and time again you're having the cliffs crash into the sea? All of that displaces water, which forces it to rise, does it not?

Dr. DUFFY. I'm pretty sure that on human time scales, those are miniscule effects.

Mr. BROOKS. Okay. Well, let's talk about ice for a moment. Where is most of the ice located on planet Earth?

Dr. DUFFY. Antarctic ice sheet.

Mr. BROOKS. And how much?

Dr. DUFFY. I don't have a number in my head.

Mr. BROOKS. Do you have a rough estimation or idea of how——

Dr. DUFFY. The amount of ice in the Antarctic ice sheet if melted would raise global sea levels——

Mr. BROOKS. I'm not asking you how much——

Dr. DUFFY. —by 200 feet.

Mr. BROOKS. Okay. You keep going and you don't answer the question. My question is, how much of the ice on the Earth is in Antarctica? I'm not asking you to expound on anything else. I'm trying to limit you to that particular question.

Dr. DUFFY. I don't know the answer.

Mr. BROOKS. Do you have any idea?

Dr. DUFFY. I wouldn't want to speculate in this forum.

Mr. BROOKS. Well, would it surprise you if it's as high as 85 to 90 percent, that that's generally where the estimates are of the total amount of ice is in Antarctica?

Dr. DUFFY. It would not surprise me.

Mr. BROOKS. And would it surprise you to know that as global temperatures rise, assuming for the moment that they do, that that actually increases the amount of ice that is collected on Antarctica?

Dr. DUFFY. That's not true, sir.

Mr. BROOKS. That's not true? Well, I made a trip down to Antarctica and met with National Science Foundation scientists, and they all agreed with global warming, and they emphasized that you're going to have an increase in the amount of ice in Antarctica because of global warming. Now, have you ever studied—I understand you studied climate but how about meteorology? Have you ever studied meteorology?

Dr. DUFFY. I have, and I'll be happy to——

Mr. BROOKS. So you understand that as the temperature——

Dr. DUFFY. We have satellite records——

Mr. BROOKS. Wait a second, please. You've answered my question. I don't want you to orate because I have limited time. If the Chair would please permit as I try to get this point across?

Chairman SMITH. Okay. Without objection, the gentleman is recognized for another 30 seconds.

Mr. BROOKS. Do you understand that as temperatures rise, more moisture is contained in the atmosphere and then that moisture in Antarctica collects on land and it takes hundreds and hundreds of years for that ice that is deposited on Antarctica to actually ever even reach the shoreline where it touches the oceans where it can affect in some way sea-level increases?

Dr. DUFFY. We have satellite records clearly documenting a shrinkage of the Antarctic ice sheet and an acceleration of that shrinkage.

Mr. BROOKS. I'm sorry, but I don't know where you're getting your information but the scientific data that I have suggests——

Dr. DUFFY. The National Snow and Ice Data Center.

Mr. BROOKS. Well, okay. I'm talking NASA and others.

Dr. DUFFY. And the National Aeronautics and Space Administration.

Mr. BROOKS. Well, I've got a NASA base in my district, and apparently they're telling you one thing and me a different thing but there are plenty of studies that have come out that show that with respect to Antarctica, that the total ice sheet, particularly that above land, is increasing, not decreasing. Now, you can make a different argument if you want to talk about Greenland or the Artic but that having been said, thank you, Mr. Chairman, for the indulgence.

Chairman SMITH. Thank you, Mr. Brooks, and the gentleman from Illinois, Mr. Lipinski, is recognized.

Mr. LIPINSKI. Thank you.

Dr. Duffy, in your testimony you state that technology will play an essential role in minimizing and adapting to the effects of climate change, something you think the U.S. government should support. You allude to the economic benefits that are likely to accrue to U.S. businesses as a result of developing these new technologies.

I agree that the government has an important role to play in helping U.S. businesses lead the world in technology to address climate change. That's why I introduced the bipartisan Challenges and Prizes for Climate Act along with 13 of my Democratic and Republican colleagues from the Climate Solutions Caucus. This bill requires the Department of Energy to organize prize competitions around climate challenges such as energy efficiency, grid energy storage, and carbon capture, and prioritizes market-ready solutions that are made in America. This is one important way the Federal Government can both incentivize and raise awareness of technology to address climate change.

I'm wondering what you think some others might be. How else can the government leverage the private sector to develop technologies and solutions that we need to address climate change?

Dr. DUFFY. Well, thanks for the question. You know, one really important measure which has been mentioned earlier would be to create the incentives, the economic incentives, to develop those technologies, and here, putting a price on carbon emissions, which after all corrects a market failure, is a very important step which would incentivize both the development and implementation of a lot of important technologies.

Mr. LIPINSKI. Any other—well, let me move on. If we—if the United States, if we don't really help lead the world in this, what do our—what do we have to lose economically? Where are we right now? Where are American businesses right now compared to the rest of the world in developing these climate solutions? And if we don't do more, what do we lose economically?

Dr. DUFFY. Well, that's a great question, and you know, in the immediate term, no country is spending more on renewable energy than China is, and you know, I would hate to lose that race to them.

You know, the other aspect of this that's very concerning to me is the potential brain drain aspect, and you know, historically, the excellence of American education and American research has been a magnet for talented people from around the world to come here and those folks have added invaluably to our country in many, many ways including economically, and when I look in the job ads section now of international scientific journals, it saddens me to see that where are all the jobs now. Well, a lot of them are in China. Most of them are in China. And again, you know, I would much prefer to see Americans investing in both the science and the technology to address this threat.

Mr. LIPINSKI. I want to focus on something a little more specific. How would you characterize the nature of geoengineering or carbon removal as a potential option to fight climate change?

Dr. DUFFY. You know, I would treat those separately. Carbon removal is a—well, carbon removal in principal actually does in fact act to reverse climate change by lowering the concentration of carbon in the atmosphere. As I mentioned in my testimony, there are rather low-tech land management methods that can remove quite a bit of CO_2 from the atmosphere, probably not as much as need to but make a really, really valuable contribution, and again, you know, those measures have some very valuable co-benefits including, as I mentioned, benefits for adaptation. Technological measures to remove carbon dioxide from the atmosphere are under development at the moment. They're very expensive, and at the moment we don't have the ability to deploy them at the scale that we need.

You also asked about so-called geoengineering, which I would characterize as measures to counteract the climatic effects of increasing greenhouse gases. I don't know anyone in the scientific community who's enthusiastic about deployment of geo engineering. I think a lot of us, however, recognize that this is something we need understand better. We need to understand the potential effectiveness, and most importantly, we need to understand the potential unintended consequences.

Mr. LIPINSKI. Thank you. I'm out of time. I yield back.

Chairman SMITH. The gentleman yields back.

And the gentleman from Florida, Mr. Posey, is recognized for his questions.

Mr. POSEY. Thank you, Mr. Chairman, and I thank the witnesses for their attendance here today.

Mr. Cass and Mr. Nordhaus, do you believe Dr. Duffy's claim that government regulation is responsible for lowering the cost of refrigerators in this country? Or do you tend to believe it might be due to competition and improved production and technical advancements?

Mr. NORDHAUS. I would say probably a bit of both, and I don't know the specific research that he is referring to, but I would assume that a significant amount of the cost savings there were not in the actual purchase cost of the refrigerator but just in the energy costs associated with running it as refrigerators have become more efficient. I do think that there's a case that various regulatory measures like EnergyStar have significantly contributed to improving the energy efficiency of refrigerators——

Mr. POSEY. We're talking about costs. Okay. Thank you.

Mr. Cass?

Mr. CASS. I think as Mr. Nordhaus emphasized, the key distinction is between the upfront cost of the product typically and then the operating cost, and what we find with regulation is that if you—and we see this now with, for instance, CAFE standards. If you require people to purchase more expensive cars that use less gas, you can claim to be saving them money. The problem is that typically they don't agree, and if they did, you wouldn't need the regulation.

Mr. POSEY. That's kind of what I thought.

Dr. Duffy, you referenced a big threat from large-scale emissions of greenhouse gases from thawing permafrost. How did the greenhouse gases get captured into the permafrost in 15 seconds or less?

Dr. DUFFY. It's dead organic matter, dead animals and plants.

Mr. POSEY. All right. What was the temperature on Earth before the last ice age?

Dr. DUFFY. Before the last ice age——

Mr. POSEY. Yes, sir.

Dr. DUFFY. —and the last interglacials? Well, similar to what it was about 100 years ago.

Mr. POSEY. You think? You don't think maybe it was 30 degrees warmer when dinosaurs roamed the Earth?

Dr. DUFFY. There certainly have been epics in the past when the global temperature was warmer than it is now, and there's evidence that during those epics there was massive release of greenhouse gases from frozen ground, previously frozen ground.

Mr. POSEY. Well, where did the greenhouse gases come from if we didn't have people to create them?

Dr. DUFFY. Oh, again, you know, the greenhouse gases that are tied up in permafrost, it's not really gases, but the carbon that's tied up in permafrost is undecayed organic matter.

Mr. POSEY. So that's a threat that would exist if people never existed?

Dr. DUFFY. It's a threat that would exist but the activities of people are unlocking that threat by warming the Arctic and causing that frozen ground to thaw.

Mr. POSEY. How many ice ages do you think we've had on this planet?

Dr. DUFFY. Dozens.

Mr. POSEY. Okay.

Dr. DUFFY. But, you know, just because it's happened before doesn't mean it's benign.

Mr. POSEY. What caused the end of the last ice age?

Dr. DUFFY. The ice ages are caused by oscillations in the Earth's orbital parameters.

Mr. POSEY. Yeah, the last one was caused by a cataclysmic collision of an asteroid on this planet, I believe.

What do you say to people who theorize that the Earth as it continues to warm is returning to its normal temperature?

Dr. DUFFY. Look, you know, if you want to characterize a temperature above today's temperature as normal, you're free to do that, but that doesn't mean that's a planet that we want to live on. If we let——

Mr. POSEY. I don't want to get philosophical. I'm trying to——

Dr. DUFFY. I'm not getting philosophical. I'm getting extremely practical.

Mr. POSEY. You're what?

Dr. DUFFY. I'm being extremely practical.

Mr. POSEY. Yeah. Well——

Dr. DUFFY. If we let the planet warm two or three degrees, we will have tens of meters of sea-level rise, and the community where I live will essentially cease to exist.

Mr. POSEY. I don't think anybody disputes that the Earth is getting warmer. I think what's not clear is the exact amount of who caused what, and getting to that is I think where we're trying to go with this Committee, just a little bit understanding of exactly how much different causes contribute to the warming that we see.

Dr. DUFFY. Look, I encourage you to look at the last assessment report of the Intergovernmental Panel on Climate Change estimated the human contribution to warming over the last 60 or 70 years is essentially equal to the observed warming. In other words, they're saying humans caused essentially all of the observed warming over the last 60 or 70 years.

Mr. POSEY. When do you think the turn was made from the 1970s prediction that we were going to have another ice age, and that was the big threat they were telling us when I was in school?

Dr. DUFFY. Well, the scientific community in the 1970s never actually widely predicted an immediate cooling. There were a few popular press articles about it but it was never something that was widely believed in the scientific community.

Chairman SMITH. The gentleman's time has expired.

And the gentlewoman from Connecticut, Ms. Esty, is recognized for her questions.

Ms. ESTY. Thank you, Mr. Chairman. I want to thank our witnesses for joining us here today for this important hearing.

I want to note, Mr. Nordhaus, I want to thank you as a member of the Transportation and Infrastructure Committee for your importantly making sure everyone on this Committee and anyone watching understands how much of the contribution towards carbon and how much of the fuel consumption, the carbon consumption is related to the transportation and the industrial sectors, and that is why it's so important on that Committee, and we welcome your testimony on that in front of the T&I Committee to make that point, but I do think it also underscores the importance of technological innovation in a variety of sectors. It cannot be an appropriate answer to say the rest of the world doesn't develop its technology or doesn't advance economically but the United States is uniquely positioned, I would say, to advance research in all of those realms, which is why we have innovation being done in the Department of Defense, which has invested heavily because 30 percent of its costs are in the cost of transportation and has recognized the value it places as well as the DOD seen the threat of sea-level rise being enormously threatening to global security as well as threatening our bases. So that is real cost right now, and if any of you have the figures on that, we can also get you to those because those are real costs and DOD is really worried about them right now, and that is going to impact taxpayer dollars as well as military preparedness, something that is not integrated often enough in this Committee.

I hail from the State of Connecticut. We are one of the RGGI states. Dr. Duffy, you have lived in several of them, California and Connecticut. In my State of Connecticut, which has decided to lean in to a lower carbon future because it sees both the short- and the long-term advantages of that, that is created with our first-in-the-nation green bank over 13,000 jobs. Those are jobs that are selling technology out of my district around the world. We have fuel cells that are being sold in Korea. We are the largest supplier of fuel cells to Korea, in part as part of that carbon transition.

If we were to lean away from that, I think about this being like insurance for a car, or better yet, insurance on your house. I've never lived in a house that has burned down but I get insurance anyway. The concerns—and there's a lot of debate, especially with my colleagues saying exactly what percentage is due to human behavior, but if the consequences, if the most extreme predictions are right, are cataclysmic for the continuation of life on Earth for human beings, then it would seem prudent that we at least take some measure of action.

So Dr. Duffy, could you talk about both the opportunity that we have from the business point of view, which is I think in part why so much of the business community leaned in on, say, the Paris Climate Accords? U.S. business leaned in and said yes, we want to support this because they see that business opportunity to sell to the entire world. And could you also talk about the research importance? We are very concerned, and we talked a lot in this Committee about China's investment across the board in research and getting ahead of us, whether it's on solar technology or other things that they will then license to the world. And Dr. Duffy, if you could talk a little bit about those business opportunities and imperatives as decision makers about what we can do?

Dr. DUFFY. Sure, I'd be happy to address that, and I'll also just echo your comments about RGGI, the Regional Greenhouse Gas Initiative, and as I'm sure you know, a number of studies have shown positive economic impacts in the nearly ten years that RGGI has been in place, and some of those positive impacts, by the way, come from improved health outcomes. I think the latest study documented $5.7 billion in savings because of improved health outcomes.

Regarding, you know, research on technologies and the business opportunity, you know, again, I think it's an important opportunity. The world as a whole is mobilizing to address this global threat. It will take global cooperation to address this threat, and you know, look, we're the United States. We should be leaders here, not followers. It's as simple as that in my view.

Ms. ESTY. Can you flag what are some of the research elements that you think the Federal Government is uniquely positioned to do the basic research? Because obviously the private sector is going to do that R&D but that basic research, whether it be fusion, which we have a variety of opinions you've heard here about fusion but certainly if we were to be successful at fusion, that would be transformative. What are some of those other areas?

Dr. DUFFY. I think in general, you know, where the Federal Government has a role is in the early-stage research where, you know, the economic payoff is doubtful or is a ways down the road and fusion would certainly be an example of that.

Ms. ESTY. Thank you, and I see I'm out of time.

Chairman SMITH. Thank you, Ms. Esty.

And the gentleman from Arizona, Mr. Biggs, is recognized.

Mr. BIGGS. Thank you, Mr. Chairman, and thank you, gentlemen, for being here to testify today. I appreciate it very much.

Mr. Cass, in your written materials you cite two studies, one by Little—or excuse me, one by Mills and one by Basera, or Barreca, I guess is—I had that wrong. They take two different approaches to mortality rates due to extreme temperature, and you said in there—let's talk about that for just a second. They both take different approaches. Why did they take different approaches? What were they looking for, and why did they traverse the path that they did?

Mr. CASS. Sure. I think the Mills study is kind of the quintessential example of ignoring adaptation. They look at different cities and assume that as temperatures change, cities will not change their response, and as a result, they produce very large cost estimates. The Barreca work I think is much more interesting and useful. They actually look at response to high temperatures over time, and so instead of just developing a homogenous response for, say, the second half of the 20th century, they say let's compare what happened in the first half to the second half or let's compare the 1960s to the 1990s, and by looking at it in those terms and by taking the adoption of air conditioning into account in particular, what they find is that by the 1990s, mortality related to heat has plummeted, and essentially they find a decline of about 80 percent from the first half to the second half, a decline of about half within the second half, and by 2004, looking at the level of air conditioning that's been adopted, the effect of heat on mortality is no longer statistically significant.

Mr. BIGGS. And have you had a chance to engage with any of these researchers to kind of find out why they took the path they took?

Mr. CASS. I've had a number of exchanges, some of them as I was doing the research, some of them more recently to sort of ask if I've missed anything or to understand the approach they're taking. You know, one response I'll hear is well, we were only trying to show what we were trying to show, so a study is we stated our assumptions and you can make of it whatever you want. Another response is to say first of all, yes, we do point out that we don't take adaptation into account, and then in fact if you look elsewhere in the report, you'll see we also provide an alternative calculation for that conclusion. So even the Mills study, for instance, actually also says well, what if we assume that cities do adapt, even just assume everyone gets as good as Dallas at dealing with heat, and just with that basic assumption they find their cost estimate I believe falls by about two-thirds. The interesting thing is that that's the more interesting finding but that's reported as an aside. It's not something the Obama EPA chose to then incorporate in the estimate of costs that it highlighted.

Mr. BIGGS. Well, I happen to come from the Phoenix metro area, which is one of the hottest areas in the United States, and if you look back 70 years ago, there was about 100,000 people. Today the metro area is five million people. So I guess my question to you is, have studies been done to determine what the variables or what—not variables but what activities have come about through adaptation to make, let's say, life more bearable in the desert?

Mr. CASS. I mean, I think the best evidence suggests air conditioning, you know, looking more broadly at the economic decision of so many people to move to the Southwest, and even today we see continued movement to the Southeast, and the analyses of mortality suggest that adopting air conditioning is the best explanation of why you don't see more mortality. I would also say just that I think there's an important lesson to be drawn from the fact that Americans looking at their options, taking everything that they wish to take into account are choosing to move further south. They are voluntarily opting for hotter temperatures, and——

Mr. BIGGS. I love the heat, by the way.

Mr. CASS. There you go. That sort of behavior again underscores that places deal with the climates that they have, and there are pros and cons to whatever climate you have. It is not correct to simply assume that if the climate changes people will behave as they did in the past.

Mr. BIGGS. Thank you, and I just have about 20 seconds left.

Mr. Nordhaus, you mentioned that you felt like we should incentivize clean fuel. What would you do to incentivize clean fuel?

Mr. NORDHAUS. Well, I think the most important thing is taking steps to drive down the cost of the underling technologies, you know, whether that's electricity technologies, transportation technologies.

Mr. BIGGS. How would you do that, though?

Mr. NORDHAUS. R&D, programs to demonstrate and commercialize some early-stage support——

Mr. BIGGS. Who would do that?

Mr. NORDHAUS. Pardon?

Mr. BIGGS. Who would do that?

Mr. NORDHAUS. I think there are a variety of measures that could be taken at both the state and federal level.

Mr. BIGGS. Thank you, Mr. Chairman.

Chairman SMITH. Thank you, Mr. Biggs.

And the gentleman from Illinois, Mr. Foster, is recognized for his questions.

Mr. FOSTER. Thank you, Mr. Chairman. Thank you to our witnesses.

First I'd like an opportunity to clear up this question about refrigerator capital costs and efficiency.

Dr. Duffy, as the only one with an actual technical background on this panel of witnesses, can you just try to clarify this a little bit?

Dr. DUFFY. Sure. The study was—the study I'm referring to was done, I don't remember when, by the California Energy Commission, and the costs in question were the purchase price of refrigerators, not the lifetime energy costs.

Mr. FOSTER. Right. And so the federal regulations regarding efficiency of refrigerators resulted in not only reduction in the electrical costs over time but also the purchase price, presumably because you can have a smaller motor, et cetera, and compressor.

Dr. DUFFY. I think that's right, and my guess is that what's happened is that at the onset—and it was both federal and state regulations. At the onset of those regulations, the companies were making refrigerators the same way they had for decades because it worked and they were making money and everything was fine, and I believe that the advent of regulations caused the engineers to take another look at it and not surprisingly they realized that gee, we progressed and we now know how to do things better than we did 20 years ago.

Mr. FOSTER. Thank you, and that's a different narrative than we often hear in this.

Staying with technical questions here, Mr. Cass, can you explain the plans that shellfish have to use air conditioning to adapt to climate change?

Mr. CASS. I'm not familiar with any. It turns out that as a relative cost of climate change, though, and it is one that EPA took into account, it barely even shows up on the chart, and so my suggestion would not be that adaptation takes care of everything as

I think I emphasized several times, there are certainly real costs to climate change but the scale of those costs does not look anything like the type of cataclysmic rhetoric that we are hearing from some members of this Committee, to some degree from some members of this panel, and also from the dollar estimates that for instance the EPA produced.

Mr. FOSTER. But—all right. There are difficulties when you talk about economic modeling of the intergenerational wealth transfers. You know, for example, underinvesting in research on low-carbon technologies, high-efficiency technology and so on, we are imposing huge costs on the next generation, and you know, those are real costs that should be modeled and are almost impossible to. On the other hand, you don't always need a complete calculation, an accurate calculation, to know that we're making big mistakes. So that from what you know of the rough estimates that have been made, is it clear that we are underinvesting in technologies actually, Mr. Nordhaus? For example, the big cuts that were proposed by the Trump Administration to research, fundamental research on energy efficiency and other green technologies, is that something which you believe is a step in the wrong direction as a society?

Mr. NORDHAUS. I would say that cutting federal investment in energy research development and demonstration is unwise.

Mr. FOSTER. Thank you.

Mr. Cass, have you seen an economic analysis that would contradict that conclusion?

Mr. CASS. I would agree with that, and my testimony specifically thanks Congress for maintaining that funding, and I think there's a good case for increasing it, but I do think it's also important to recognize that just as we ask the climate scientists to provide the best possible science on climate, we also need to ask economists to provide the best possible economics on climate, and if you look at the economics for climate change that are being produced, the cost estimates that they're delivering are not defensible, and so——

Mr. FOSTER. How do you economically model, for example, the costs of the extinction of a species?

Mr. CASS. I think that's very difficult to model economically, and I think that we need to be realistic about what they are, and so when you describe the huge costs that we're imposing on future generations, we need to define what those are, and certainly neither EPA nor GAO managed to find those.

Mr. FOSTER. So you would advocate then for more effort in more accurately defining the climate—the cost of future climate change?

Mr. CASS. Yes, absolutely, and I think it's critical in doing that to emphasize that adaptation is not something to be put to the side. Adaptation is the central question to what the costs will be and in many respects to what the best policy responses will be. We need to understand what are the things we're going to adapt to fairly naturally, what are the things we're going to adapt to but with cost. Air conditioning, for instance, is not free, and what if anything are the things that maybe we will have difficulty adapting to and we need contingency plans for. I have not heard good definitions of things that it's difficult to conceive of society adapting to but I certainly think that's an exercise we should be asking about.

Mr. FOSTER. Any comments, Mr. Nordhaus?

Mr. NORDHAUS. Yeah, I think that there are just huge uncertainties both ways when we try to look out a century and think about, you know, what we can adapt to, what we can't adapt to, what the costs of mitigation will be. They're just—we don't know. So you have to——

Mr. FOSTER. And yet you both conclude that we're under-investing as a society in——

Mr. NORDHAUS. Absolutely, and I would just make one other point, which is that I do want to—there are very difficult to quantify if not unquantifiable risks of quite rapid impacts, and I think as Mr. Cass has also recognized, very rapid change would be much more costly and difficult to adapt to, and we just don't know, and I think it will—I don't think more climate science is likely to help us better understand the likelihoods on timeframes that we would need to take action to address them, so that's not an argument against climate science but we should understand what sorts of uncertainties we're likely to be able to resolve and what sorts of uncertainties we're unlikely to resolve.

Mr. FOSTER. Thank you, but I think it's interesting that you both agree that actions like the recent cancellation of NASA's carbon monitoring system are actually also steps in the wrong direction. We need more information on the time scale of which this problem will bite us.

Thank you, and I yield back.

Chairman SMITH. Thank you, Mr. Foster.

The gentleman from Texas, Mr. Weber, is recognized.

Mr. WEBER. Thank you, Mr. Chairman.

Mr. Cass, you mentioned the study by the EPA that found that Pittsburgh extreme heat and mortality will rise exponentially beyond levels even in Phoenix or Houston, so I've got a couple of questions for you. Is it true that the closer to the equator you get, the warmer it is?

Mr. CASS. Generally speaking, I believe that's right.

Mr. WEBER. You believe that's right from your geography back in the sixth grade?

Mr. CASS. And traveling south from time to time.

Mr. WEBER. Well, you need to come to Galveston and spend lots of money.

I owned an air conditioning company for over 35 years, so when you start—and by the way, we loved seasons changing. We loved heat in Texas. And I can tell you from firsthand experience a couple things being in the business 35 years. We're not experiencing mass casualties. Now, Congressman Biggs from Arizona said that he loved the heat too. Over in Arizona they've got a dryer heat. Of course, we have the more humid heat. So I want you, Mr. Cass, to expand on what's wrong with two things if you can. I realize one's more scientific and one's a little less. What's wrong with the study of prediction of mortality in Pittsburgh, which is arguably further up north and a lot further away from the equator than we are in Texas, that they think there would be 75 times more mortalities in Pittsburgh than in Phoenix or in Houston? Number one, what's wrong with that study? And number two, isn't that a big hyperbole to create some kind of need to really push forward on more regulations?

Mr. CASS. Thank you. The technical way of describing the problem I think is to say that the study assumes all things are held constant, and of course, that's traditionally how we expect economic analysis——

Mr. WEBER. But let me interject here real quick. So if that was true, we're closer to the equator. If it was getting hotter in Pittsburgh, would it be getting hotter in Texas? Would that be a safe assumption?

Mr. CASS. Yes.

Mr. WEBER. And at the same rate?

Mr. CASS. There are variations but generally speaking——

Mr. WEBER. Okay. Keep going.

Mr. CASS. So I think the way to understand the problem is that they identified an effect of extreme heat days in Pittsburgh on mortality and assume that a day of that heat level will always have the same effect even if Pittsburgh's climate changes. That's a very poor assumption to make because we can see what places with warmer climates look like and how they respond to temperatures, and we know that they respond differently from Pittsburgh, and so if you were going to try to project how Pittsburgh would respond to a warmer climate, you need to look at how people in warmer climates respond. You can't assume that Pittsburgh is going to respond as if it still had——

Mr. WEBER. You'd buy adequate air conditioning. I can tell you from experience how that happens in the Gulf Coast.

Mr. CASS. That's exactly right. And I think it's important to point out when we talk about adaptation that, you know, technological adaptation—and certainly that's the title of the hearing—is only one form of adaptation. There are biophysical adaptations. People do get used to the heat. There are behavioral adaptations. There are economic adaptations. There are social adaptations.

Mr. WEBER. There's probably a certain number of people in Pittsburgh who don't buy air conditioning because of the cost because they figure they can tough it out in the warmer times because it has a cooler climate more often more so than Texas does, and then even though 71 degrees to us is very, very cool—you know, Texas can be 95 to 100, 105—and when they get caught with higher temperature, in my opinion, that should be 90, 95 or 100, depending on how much ventilation's in that home, then people could suffer heat strokes and be in real dire danger. Do you think that's part of the hype, trying to force more regulations on the energy industry?

Mr. CASS. So just to clarify, the 71 degrees is the low, so a day with a low of 71 is a warm day, but I think you're exactly right that people in Pittsburgh are not going to respond to one very warm day a year the way they would respond if they had 30, and so you'd expect to see them behave differently in the context of a changing climate. I do think that part of the impetus for not including good analyses of adaptation in topline cost estimates is to create large topline cost estimates, and the fact that a lot of these analyses actually do provide analyses with adaptation but put those off to the side as an alternative case instead of as the main case I think is one of the problems.

Mr. WEBER. Well, I will tell you——

Dr. DUFFY. If I could offer a comment on——

Mr. WEBER. No. I'm sorry, Mr. Duffy. I'm running out of time. I can tell you from experience, 35 years in the air conditioning business, that the higher the efficiency ratings went up and the price was driven up, the less likely customers were to buy. They were hard pressed to say they'll spend $6,000 or $7,000 for a new air conditioning system. All of a sudden you've created one now where you've got to be more efficient, better compressors and more crawl space, and now those are 8,000 or 9,000. They're having trouble coming up with the six much less the eight or nine. So what do they do? They fix the old clunker that's terribly energy inefficient and keep it going for yet another year.

Mr. Chairman, I yield back.

Chairman SMITH. Thank you, Mr. Weber.

And the gentleman from Pennsylvania, Mr. Lamb, is recognized for his questions.

Mr. LAMB. Thank you, Mr. Chairman, and before I ask any questions, I'll just testify as a southwestern Pennsylvanian that the good people of Pittsburgh are going to be just fine. We have throughout our history and I think our record of sports championships helps testify to the toughness that we have. Obviously we're very concerned about how costly these changes will be, especially in a part of the country like ours. People are elderly, and the costs of cooling your home an extra 5 degrees will be difficult for people living on Social Security and pensions, but I just wanted to make that comment.

Also, Mr. Chairman, if it's all right, I would like to introduce a study without objection. It is from the NASA Jet Propulsion Laboratory in California. It addresses the issue of ice losses in the Antarctic that was discussed earlier. Dr. Duffy was asked several questions about it, and this is just meant simply to show that it is a complicated issue and that it was government-funded NASA research that has really helped us improve our understanding of this complicated problem.

Chairman SMITH. Without objection, that will be made a part of the record.

[The information follows:]*************** COMMITTEE INSERT ***************

Mr. LAMB. Thank you, Mr. Chairman.

Now, Dr. Nordhaus—or Mr. Nordhaus, I'm sorry—if I could ask you a question about the importance of America's nuclear plants. Your testimony noted that it's important to keep these plants open, and you noted a few things: state and federal clean energy standards, intervention at FERC, and other measures that could do this. Could you just briefly expand on that? What are some other options we have to help these nuclear plants that are at risk of closing?

Mr. NORDHAUS. I think properly valuing both the reliability and the low-carbon nature of the electricity they produce, and there are a bunch of different ways to do that. I think that many states with nuclear plants that are threatened with closure also have renewable portfolio standards, and if we transition those to clean energy standards, we could both significantly raise the bar in terms of what the requirements for zero carbon energy in those states was, keep those plants online for quite a while longer, and at some point if it makes sense to close them and replace them with other—we'll know they'll be replaced with other zero-carbon options as opposed to fossil fuel-powered options so——

Mr. LAMB. Are you aware of efforts in New Jersey, Illinois, New York to do exactly that? Do you support those efforts?

Mr. NORDHAUS. Yeah, I support all of those efforts, and again, would only suggest that we'd be much better served moving from a sort of one-off bailing out nuclear plants plant by plant to a more broader strategy to increase low-carbon energy on the grid by keeping all of our nuclear plants operating.

Mr. LAMB. I also wanted to ask about R&D spending. I've read a report recently from Boston Consulting Group, and it suggests that the United States still leads the world in frontend basic R&D spending like in basic research but that where we have been surpassed by China is in actually bringing these technologies to the market, and now they're spending more than us in that regard. Can you talk about what we could do at our national labs or elsewhere to close that gap and try to get more American-funded research to the market in America and elsewhere?

Mr. NORDHAUS. Yeah, I think there's an old idea about R&D, which is that there's this sort of thing called basic science that you put in a box and you fund that and then sort of private firms take that and do things with it. I think that when you look at the Chinese model, it's very much state led. I think that in the United States when you really look at most of our greatest successes, certainly in energy but in many, many other technological arenas, what we've really seen are public-private partnerships where there is significant public support for applied research. Often first-of-a-kind technologies are quite costly to build, whether it's your first nuclear plant or your first big carbon capture facility, and those things do require public support. The private sector isn't going to do it alone.

Mr. LAMB. And just lastly, before we run out of time, you had mentioned earlier the idea of federal and state combinations. I think you mentioned a federal transportation project or demonstration when you were asked about clean fuel earlier and how we might bring that to market. Could you just elaborate on that a little bit?

Mr. NORDHAUS. Yeah. I think that there are a variety of efforts, longstanding efforts actually, to sort of get these technologies to market, and it's been both state and federal policy that sort of have gotten us to the point where we do have cleaner fuels——

Mr. LAMB. Do you have like a specific example to illustrate that?

Mr. NORDHAUS. You know, going back even to the 1990s, there was a big federal partnership with the automakers on battery technology that really sort of established the trajectory that we're on now in terms of electric vehicles, so that would be one.

Mr. LAMB. Thank you, Mr. Chairman. I yield back.

Chairman SMITH. Thank you, Mr. Lamb.

And the gentleman from Texas, Mr. Babin, is recognized.

Mr. BABIN. Yes, sir. Thank you, Mr. Chairman. Thank you to the witnesses as well.

Mr. Nordhaus, it is unrealistic to assume that we will be able to rely on renewable energy like wind and solar in the near future for all of our energy needs. Is that a true or false statement?

Mr. NORDHAUS. That would be my view.

Mr. BABIN. Okay. How do we decide when it's time to reduce wind and solar subsidies to allow the market to take over?

Mr. NORDHAUS. I think that with mature wind and solar technologies, which is mostly what we're subsidizing now, there is general agreement including among proponents of those technologies that they are competitive in many contexts with fossil fuel technologies. I think we're probably at the point where we ought to put that proposition to the test and scale back subsidies. Now, I do think that there are probably a range of advanced renewable technologies that we may want to continue to provide some support for, but when you're looking at cheap solar, 15 percent efficiency solar panels that are being mass produced in China, I'm not quite sure why we're, you know, paying, you know, substantially continuing to subsidize them.

Mr. BABIN. I got you, and I agree with you 100 percent.

Dr. DUFFY. I'd be happy to add a comment on that if I may.

Mr. BABIN. Well, I'm not through just yet. We had the Department of Energy Secretary here just last week, and we brought out the fact that some federal agencies had formally been articulating and reporting on the amount of subsidies for solar versus fossil fuel versus wind, et cetera, and it was astounding to see just a few years ago like 4 years ago that we were spending something like 15 times more subsidizing solar than we were, say, fossil fuels, in fact, even 100 times in some cases, and all of a sudden this agency that was reporting this went silent. We're not able to see those reports over the last few years, and we don't know whether they don't want the public to see these huge discrepancies or what the reason is, but Secretary Perry said that he was going to look into this and start printing these reports out again. Thank you.

Thank you. Why is it important, Mr. Nordhaus, that the United States not stand in the way of developing countries' efforts to build and improve infrastructure even if it means more fossil fuel consumption?

Mr. NORDHAUS. Well, as I noted earlier, when it comes to infrastructure, that's what makes us adaptable and resilient to a changing climate and to just existing climate extremes, so if you're concerned about the impacts of climate change on poor populations in the developing world, the most important thing that they can do certainly over the next couple of decades is build infrastructure, and right now a lot of that infrastructure still requires fossil fuels, so we should be clear-eyed about the tradeoffs between mitigation and adaptation in those particular contexts.

Mr. BABIN. Thank you.

And Mr. Cass, in your testimony you mentioned that the Mills study included an alternative analysis from its main findings that excluded human adaptive response to temperatures. Do most temperature studies that you have analyzed come with such a disclaimer to the public that human ability to adapt is not considered a factor?

Mr. CASS. Usually the study itself will state that, and I would say fairly clearly if you go and find the original report and read it, you can understand what they're doing. I think the problem is that by the time it gets summarized up to the GAO summary to policymakers, certainly by the time it gets reported in the newspaper, that kind of context is either lost entirely or put down at the bottom when in fact it's the very heart of the issue.

Mr. BABIN. And then also, back to you, Mr. Nordhaus, you testified that the U.S. carbon emissions are lower today than what would have been mandated by the Waxman-Markey legislation in 2009 that failed to pass Congress. What has been the primary driver in this reduction?

Mr. NORDHAUS. The biggest single driver has been the shale gas revolution, which I would note, you know, is a classic example of the sort of public-private partnership to develop, commercialize cheap scalable technology that we need a lot more of. I think that I will also note that once upon a time, we thought of natural gas as a bridge fuel in the power sector from high-carbon to low-carbon intensity. I think when you look at the record, having looked at generation shares in the power sector over the last decade, I think there's a pretty strong case that natural gas is mostly doing exactly that, that it has been displacing coal, and that in more recent years a lot of natural gas generation has been displaced by wind, which is the other, the second largest driver of falling emissions in the power sector.

Mr. BABIN. And I can vouch for that because my home district of southeast Texas had a brand-new biomass plant meant to take wood products and convert them into electricity to be sold on the grid, and yet within just a few short years later this brand-new plant is now sitting idle because of the cheap natural gas feedstocks that we have today, so anyway, thank you very much, and Mr. Chairman, I'll yield back.

Chairman SMITH. Thank you, Mr. Babin.

The gentleman from Florida, Mr. Crist, is recognized.

Mr. CRIST. Thank you, Mr. Chairman.

I am from Florida. I first want to thank the witnesses for being here today. I appreciate your time. I represent on the west coast of Florida Pinellas County, which is the St. Petersburg, Clearwater area. Pinellas County happens to be a peninsula, and Florida, as you're aware, is a peninsula also, and some make the argument that Florida may be the state that is most susceptible to rising sea levels.

Having said that, Dr. Duffy, I'd like to ask you, what would you say are the three greatest causes of climate change, if you could do that?

Dr. DUFFY. Well, there's really two major causes, and the first is—well, human emissions of greenhouse gases generally and that comes from two sources. One is burning of fossil fuels, and the other is land-use practices like deforestation and also agriculture. Agriculture historically has released a large quantity of carbon dioxide into the atmosphere.

Mr. CRIST. How so?

Dr. DUFFY. Through tilling of soil. Agriculture also releases other greenhouse gases besides CO_2: methane, nitrous oxide, methane through livestock largely, nitrous oxide through fertilizers. Agriculture food production is a very significant source of human greenhouse gas emissions.

Mr. CRIST. You said that the first cause is human emissions? Is that how you described it?

Dr. DUFFY. Yes, sir, and within the category of human emissions, the biggest contribution historically has been burning of fossil fuels.

Mr. CRIST. And what would be the simplest way to stem the tide of that level of fossil fuel burning?

Dr. DUFFY. Well, what needs to happen is adoption of carbon-free energy sources as we've been discussing here this morning.

Mr. CRIST. And which do you think are the most effective?

Dr. DUFFY. Well, as I said, you know, I would argue for accelerated deployment of the technologies we have today, which are mainly wind and solar. I think Mr. Nordhaus has argued persuasively for the need to keep nuclear power in the mix, and I agree with that, but those are the technologies that we have today. I do also support the development of new technologies and new ideas.

Mr. CRIST. You know, when you think about how much we utilize coal, fossil fuels as an energy source, and automobiles are, I assume, a big contributor to carbon emissions as well, if we had all cars become electric, would that have a significant impact on the reduction of emissions?

Dr. DUFFY. It would. In the United States, the transportation sector, which is of course more than just cars, the transportation sector contributes roughly 25 percent of our greenhouse gas emissions. In California where I've spent most of my life, it's actually much higher proportion, almost 50 percent, 40, 50 percent. You know, certain——

Mr. CRIST. Because of the amount of automobiles?

Dr. DUFFY. We drive a lot in California. You know, I agree with Mr. Nordhaus that, you know, certain parts of the transportation sector are pretty easy to electrify, and cars are certainly an example of that. I mean, we have electric cars now. They're treat. I drive one. Other parts of the transportation sector will be much, much more difficult. We haven't mentioned aviation but that's probably the best example.

Mr. CRIST. Great. Thank you very much. I appreciate your time. I yield back.

Chairman SMITH. Thank you, Mr. Crist.

And the gentleman from California, Mr. Takano, is recognized.

Mr. TAKANO. Thank you, Mr. Chairman.

Mr. Duffy, did you have anything more to say about renewables, claims being made about the viability of renewables?

Dr. DUFFY. Yeah. Well, on the economics, I mean, there are—and I guess there's conflicting figures but fossil fuels have certainly been heavily subsidized as well, and I've seen figures suggesting that fossil fuels are actually more heavily subsidized than renewables.

The other thing that's important to mention about cost is that for fossil fuels, there's tremendous environmental costs associated with the use of fossil fuels, which are not reflected in the price, and we've been focusing today on the climate consequences of fossil fuels but there's also very, very important public health consequences, and just to give you an example, particulate pollution from use of coal even today kills about 10,000 Americans a year. Now, that number has come down dramatically in large part because of EPA regulation on coal-burning power plants, and I'd also add to that that if you look and you compare mortality from coal use in China to mortality from coal use in the United States, and I'm not talking about different amounts of coal being used, I'm saying per ton of coal burned, the mortality in the United States is 20 times less than that in China, and that's because we have very effectively and cost-effectively regulated the air pollution from coal burning.

Mr. TAKANO. I'm curious about something. I struggle with this idea of nuclear power being a carbon-free source. I mean, I hear you saying that you agree, Mr. Nordhaus, that you don't want to rule it out as part of the mix that we need to employ to reduce the amount of carbon we emit. Is there—but isn't there some problem that we have with managing the spent fuel? Isn't there some enormous subsidy that the government will have to—or at least use the leverage of its power to force communities who don't really want to have the risk of the spent fuel in their backyard or nearby for those communities that do produce the fuel? I mean, presumably everybody would benefit from it. There's some generalized socialized good that comes from it but how do we think about this?

Mr. NORDHAUS. Well, look, nuclear power is not without its issues, and you mentioned disposal of spent fuel. There's, you know, also legitimate concerns about weapons proliferation. I will say, you know, a couple points though. I mean, it can be used effectively. At one point I think the country of France generated 80 percent of their electricity from nuclear power. I would also say that, you know, the safety issues with nuclear power have been greatly exaggerated, not to say they don't exist but if you look at the actual safety record of nuclear power in the United States, I don't think there's been one human death attributed to nuclear power in the United States, and that's remarkable. And as I said, fossil fuels are extraordinarily dangerous. You know, even solar panels, there's some amount of mortality. People fall off roofs and so on.

Mr. TAKANO. This is a much deeper conversation, I would say, but a recent report by the Department of Defense on climate risk to DOD infrastructure that was recently submitted to Congress was determined to have had significant edits made from a draft version from December 2016. Major changes in the report include omission of references to climate change.

Dr. Duffy, how important is it to ensure that accurate scientific assessments regarding impacts due to climate change be made available to the broader public and to our military specifically?

Dr. DUFFY. Thanks for the question. You know, the military leaders that I've talked to clearly recognize the threat that global climate change poses for their operations and their war-fighting capabilities, and I think that that threat needs to be recognized, and I would hate to see our fighting men and women placed at unnecessary risk because we're afraid to confront this threat.

Mr. TAKANO. Well, what are the dangers of playing down the role of climate impacts on infrastructure, both military and non-military, to try and stay—in order to try and stay, quote, unquote, apolitical?

Dr. DUFFY. You know, the danger is that we don't build the right infrastructure, you know, and we do—we have—we face a backlog of decaying infrastructure in this country, infrastructure of all sorts, not just transportation infrastructure—energy infrastructure and so on. We need to invest in new infrastructure, and as we do that—and I've been involved in some major water infrastructure projects in California and, you know, these major physical infrastructures typically are designed to last 50 or 100 years, and you know, what we did when we designed water infrastructure in California is to think ahead and what is the climate and hydrology of the next 50 or 100 years going to look like, and that's what the water agencies in California do and that's what we should do generally. We need to design the infrastructure around the climate of the future, not the climate of the past.

Mr. TAKANO. Thank you. My time is up.

Chairman SMITH. Thank you, Mr. Takano.

Let me thank you all for being here today. I think this was a very worthwhile discussion of various challenges that we face, and I was really pleased to see more agreement than disagreement on the need and reliance upon innovation and technology in the future to address climate change as well. I appreciate the testimony and the manner today. You all reflected the moderation and humility that Mr. Nordhaus mentioned, and we have not always had that when we discussed this subject, so I appreciate both, as I say, what you said and how you said it. So thanks again for being here.

The record will remain open for two weeks for additional written comments and questions from Members, and we stand adjourned.

[Whereupon, at 12:09 p.m., the Committee was adjourned.]

Appendix I

Answers to Post-Hearing Questions

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Phil Duffy

HOUSE COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY

"Using Technology to Address Climate Change"

Dr. Phil Duffy, President and Executive Director, Woods Hole Research Center
Questions submitted by Rep. Eddie Bernice Johnson, Ranking Member, Committee on Science, Space, and Technology

1. **Has global sea level rise increased at a constant rate over the past 100 years?**

Global sea level has risen at an accelerating, rather than constant, rate over the past 100 years. The figure below illustrates a four-fold (or more) acceleration in sea-level rise over the last century. The rate of sea-level rise averaged 0.6 mm yr-1 from 1900 to 1930, increasing to at least 2.6 mm yr-1 from 1993-2015. The Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report estimates the rate of sea level raise between 1993 and 2010 at 3.2 mm/yr, even higher than that illustrated below, and suggesting a more than 5x acceleration in the rate of sea level rise.

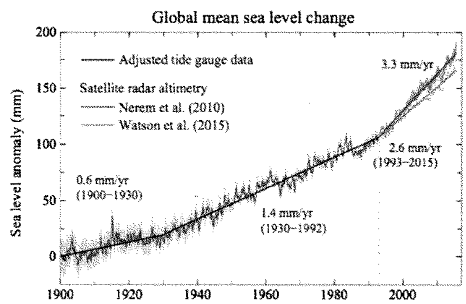


Figure 29. Estimated sea level change (mm) since 1900. Data through 1992 are the tide-gauge record of Church and White (2011) with the change rate multiplied by 0.78, so as to yield a mean 1901–1990 change rate of 1.2 mm year^{-1} (Hay et al., 2015). The two estimates for the satellite era (1993–2015) are from Nerem et al. (2010, updated at http://sealevel.colorado.edu) and Watson et al. (2015).

Source: Hansen, James, et al. "Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 C global warming could be dangerous." *Atmospheric Chemistry and Physics* 16.6 (2016): 3761-3812.

a. Do the trends in mean global sea level rise match the trends in global carbon emissions in the past 100 years?

Recent observed sea levels are consistent with the expected effects of human-caused global warming. Sea levels are rising in large part due to melting land ice and to thermal expansion of the ocean water, both of which are a consequence of increasing atmospheric greenhouse gases (GHG) resulting from human activities (fossil fuel burning and land use change). The acceleration in the rate of sea-level rise is a lagged response to warming resulting from the long-term buildup of GHG in the atmosphere. There is not expected to be a 1:1 relationship between global carbon emissions and sea level. The rate of sea level rise corresponds more closely to temperature than to annual carbon emissions, but even this relationship is not linear.

b. What are the primary contributing factors to sea level fluctuations since the turn of the 20th century?

The table below, from the IPCC's Fifth Assessment Report, estimates the global mean sea level (GMSL) rise budget for three different time intervals. Both observed and modeled GMSL contributions show that melting of land ice and thermal expansion of the ocean together are the dominant cause of sea-level rise in the 20th and 21st centuries.

Global Mean Sea Level Budget (mm yr-1), 1901-2010

Table 13.1 | Global mean sea level budget (mm yr^{-1}) over different time intervals from observations and from model-based contributions. Uncertainties are 5 to 95%. The Atmosphere–Ocean General Circulation Model (AOGCM) historical integrations end in 2005; projections for RCP4.5 are used for 2006–2010. The modelled thermal expansion and glacier contributions are computed from the CMIP5 results, using the model of Marzeion et al. (2012a) for glaciers. The land water contribution is due to anthropogenic intervention only, not including climate-related fluctuations.

Source	1901–1990	1971–2010	1993–2010
Observed contributions to global mean sea level (GMSL) rise			
Thermal expansion	–	0.8 [0.5 to 1.1]	1.1 [0.8 to 1.4]
Glaciers except in Greenland and Antarctica[a]	0.54 [0.47 to 0.61]	0.62 [0.25 to 0.99]	0.76 [0.39 to 1.13]
Glaciers in Greenland[a]	0.15 [0.10 to 0.19]	0.06 [0.03 to 0.09]	0.10 [0.07 to 0.13][b]
Greenland ice sheet	–	–	0.33 [0.25 to 0.41]
Antarctic ice sheet	–	–	0.27 [0.16 to 0.38]
Land water storage	–0.11 [–0.16 to –0.06]	0.12 [0.03 to 0.22]	0.38 [0.26 to 0.49]
Total of contributions	–	–	**2.8 [2.3 to 3.4]**
Observed GMSL rise	**1.5 [1.3 to 1.7]**	**2.0 [1.7 to 2.3]**	**3.2 [2.8 to 3.6]**
Modelled contributions to GMSL rise			
Thermal expansion	0.37 [0.06 to 0.67]	0.96 [0.51 to 1.41]	1.49 [0.97 to 2.02]
Glaciers except in Greenland and Antarctica	0.63 [0.37 to 0.89]	0.62 [0.41 to 0.84]	0.78 [0.43 to 1.13]
Glaciers in Greenland	0.07 [–0.02 to 0.16]	0.10 [0.05 to 0.15]	0.14 [0.06 to 0.23]
Total including land water storage	**1.0 [0.5 to 1.4]**	**1.8 [1.3 to 2.3]**	**2.8 [2.1 to 3.5]**
Residual[c]	**0.5 [0.1 to 1.0]**	**0.2 [–0.4 to 0.8]**	**0.4 [–0.4 to 1.2]**

Notes:

[a] Data for all glaciers extend to 2009, not 2010.

[b] This contribution is not included in the total because glaciers in Greenland are included in the observational assessment of the Greenland ice sheet.

[c] Observed GMSL rise – modelled thermal expansion – modelled glaciers – observed land water storage.

Source: Table 13.1, IPCC WG1 AR5, Chapter 13

2. Please describe how Antarctic ice sheet extent has varied in recent years.

The Antarctic ice sheet has been losing ice during the last two decades, and that net loss has been accelerating. The figure below illustrates an acceleration of the rate of mass loss of the Antarctic ice sheet through 2012.

Acceleration of Antarctic Ice Sheet Decay

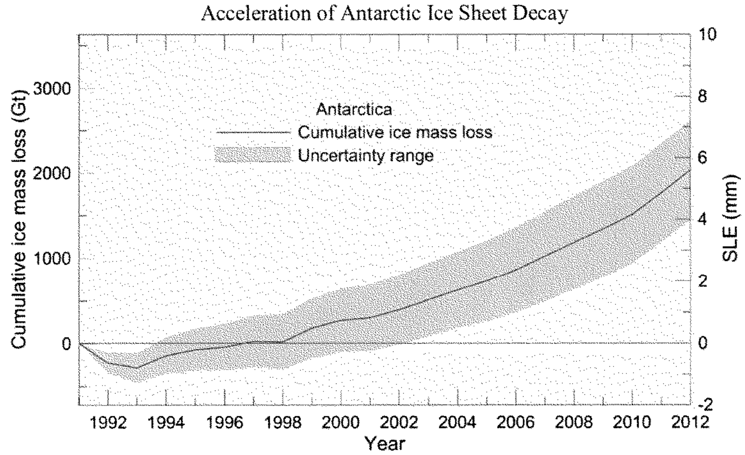


Figure 4.16 | Cumulative ice mass loss (and sea level equivalent, SLE) from Antarctica derived as annual averages from 10 recent studies (see main text and Appendix 4.A for details).

Source: Figure 4.16, IPCC WG1 AR5, Chapter 04.

The IPCC's Fifth Assessment Report concludes the following:

"The Antarctic ice sheet has been losing ice during the last two decades (*high confidence*). There is *very high confidence* that these losses are mainly from the northern Antarctic Peninsula and the Amundsen Sea sector of West Antarctica, and *high confidence* that they result from the acceleration of outlet glaciers.

The average rate of ice loss from Antarctica *likely* increased from 30 [–37 to 97] Gt yr–1 (sea level equivalent, 0.08 [–0.10 to 0.27] mm yr–1) over the period 1992–2001, to 147 [72 to 221] Gt yr–1 over the period 2002–2011 (0.40 [0.20 to 0.61] mm yr–1).

A more recent assessment (published in *Nature* on June 13, 2018) weighed the results of 24 studies of antarctic ice loss and found that the rate of ice loss has increased 3x in the past 10 years.

a. Can you please address the discrepancy with recently reported Antarctic ice sheet gains compared to an increase in global atmospheric and ocean temperatures?

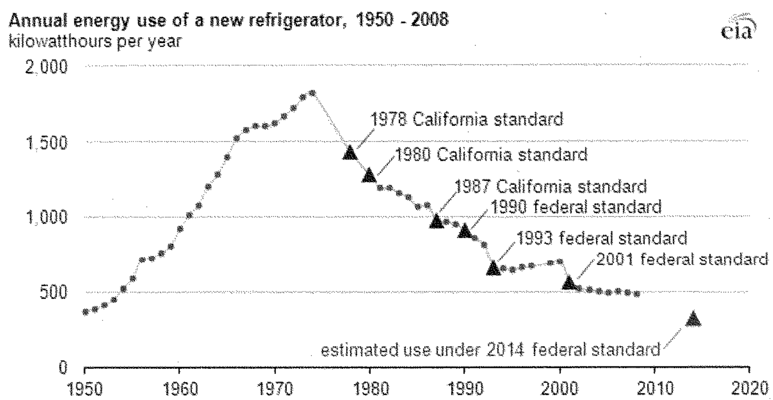
A 2015 NASA study based on satellite altimetry concluded that the Antarctic ice sheet was gaining ice overall. This conclusion contradicted those of both earlier and later studies. The 4th National Climate Assessment, released by the Trump administration in November 2017, weighed evidence available at the time and concluded that the Antarctic ice sheet is shrinking.

b. Do ice sheet gains disprove the overall levels of rapid ice loss recently in the Antarctic?

Gains in some regions of the Antarctic ice sheet are not enough to overcome losses of ice in other regions.

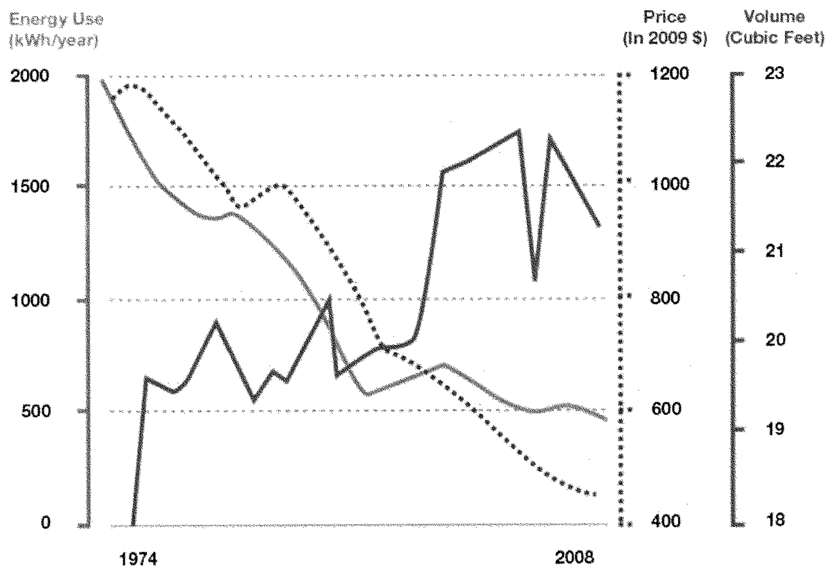
3. How did energy conservation regulations for refrigerators impact the energy consumption, price, and size of refrigerators?

Starting in the mid-1970s, California and the United States issued a series of energy conservation regulations for home refrigerators. As a result, the average energy demand per new refrigerator declined dramatically, from about 2,000 kilowatt hours used per year to about 500 kilowatt hours per year.



Source: EIA (https://www.eia.gov/todayinenergy/detail.php?id=10491)

The two figures included here on home refrigerator appliance history demonstrate that refrigerator volume has increased while the purchase price has fallen over the same historical time period.



Source: U.S. Department of Energy (https://www.energy.gov/eere/buildings/articles/refrigerator-standards-saveconsumers-billions).

a. What impact have refrigerator standards had on the American consumer?

The history illustrated here suggests that regulation has led to cheaper and more efficient refrigerators.

b. Did the presence of regulations hinder or enhance the development of new refrigerators?

It appears that regulation had a role in stimulating innovation in refrigerator design.

Appendix II

Additional Material for the Record

STATEMENT SUBMITTED BY DR. JUDITH CURRY

STATEMENT TO THE COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY OF THE UNITED STATES HOUSE OF REPRESENTATIVES

Hearing on Using Technology to Address Climate Change

16 May 2018

Judith A. Curry
Climate Forecast Applications Network
Georgia Institute of Technology
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Major points:

- There are multiple causes of climate variability and change, and climate is just one element of the complex causes of vulnerability of human and natural systems.
- In adapting to climate variability and change, we need to acknowledge that we cannot know exactly how the climate will evolve in the 21st century, we are certain to be surprised and that we will make mistakes along the way.
- Possible scenarios of incremental worsening of weather and climate extremes don't change the fundamental storyline that the U.S. is highly vulnerable to current extreme weather and climate events and has an adaptation deficit relative to the current climate state and historical extreme events.
- Rather than 'bouncing back' from extreme weather and climate events, we can 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices.
- A focus on local policies that support resilience and anti-fragility avoids the hubris of thinking we can predict the future climate.
- Rather than negotiating an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent.
- Climate models are not the only, or best, way to generate future scenarios of regional climate change. Current climate model predictions neglect important aspects of natural variability.
- All scientifically plausible scenarios of future climate change need to be on the table to inform adaptation, not just those selected by a particular heuristic, e.g. emissions scenarios.
- On regional and decadal time scales, the greatest vulnerability to climate change is not associated with the smooth long-term trend but rather with rapid shifts in frequencies and intensities of extreme weather and climate events that are driven by natural internal climate variability.
- Sea level rise is an issue for which anticipatory adaptation is justified by our scientific understanding of the direction (if not the magnitude) of future sea level change.
- Large-scale ocean circulations can cause regional sea level rise to exceed global mean sea level rise by an order of magnitude.
- In many of the locations that are most vulnerable to sea level rise, natural oceanic and geologic processes plus land use practices are the dominant causes of current local sea level rise problems.
- The focus of climate science on mitigation-relevant science (e.g. attribution, sensitivity) has diverted resources away from regional climate dynamics and prediction of extreme events on weekly to seasonal time scales that would support tactical and strategic adaptation decisions.

STATEMENT TO THE
COMMITTEE ON SCIENCE, SPACE AND TECHNOLOGY
OF THE UNITED STATES HOUSE OF REPRESENTATIVES

Hearing on
Using Technology to Address Climate Change

16 May 2018

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I thank the Chairman and the Committee for the opportunity to offer testimony today on 'Using Technology to Address Climate Change.' I am Professor Emeritus of the School of Earth and Atmospheric Sciences at the Georgia Institute of Technology. I have devoted four decades to conducting research on a variety of topics related to weather and climate. In recent years my focus has been on uncertainty and the interface between climate science and policy. As President of Climate Forecast Applications Network LLC, I have been working with decision makers to use weather and climate information to reduce vulnerability to extreme weather and climate events.

In 2014, I was privileged to host to host the *UK-US Workshop on Climate Science Needed to Support Robust Adaptation Decisions*.[1] The Workshop participants included some of the world's leading thinkers and practitioners on climate adaptation. The Workshop was motivated by the recognized gap between what science is currently providing in terms of information about climate variability and change, versus the information desired by decision to make robust development and adaptation plans for managing climate-related risks and responding to opportunities. The focus was on timescales out to 2050 and regional scales. The Workshop addressed perspectives from the public and private sectors[2] on climate adaptation, strategies for robust decision making,[3] limits of climate models,[4] and broadening the portfolio of climate information.[5] The insights from this Workshop provide the framing for my testimony.

Adapting to climate change

In context of the debate on climate change, two overarching policy response options have been articulated:

1. Mitigation of climate change through reduction of greenhouse gas emissions
2. Pre-emptive adaptation to climate change through improved infrastructure, land use practices and management of resources.

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[1] https://judithcurry.com/2014/02/10/uk-us-workshop-on-climate-science-needed-to-support-robust-adaptation-decisions/
[2] https://judithcurry.com/2014/02/12/uk-us-workshop-part-ii-perspectives-from-the-private-sector-on-climate-adaptation/
[3] https://judithcurry.com/2014/02/14/uk-us-workshop-part-iii-strategies-for-robust-decision-making-for-climate-adaptation/
[4] https://judithcurry.com/2014/02/18/uk-us-workshop-part-iv-limits-of-climate-models-for-adaptation-decision-making/
[5] https://judithcurry.com/2014/03/19/uk-us-workshop-part-v-broadening-the-portfolio-of-climate-information/

In strategizing about both mitigation and adaptation to climate change, it is important to recognize that both policy options exist in context of a broad and complex policy environment:

1. Mitigation impacts global, national and regional policies on energy, transportation, agriculture and environmental quality, with concomitant issues related to economics and security
2. Adaptation is in response to both human caused and natural climate variability and weather extremes, and is driven by local vulnerabilities, economic capacity, cultural values and governance. The impacts of weather and climate extremes are exacerbated by growing populations and the associated resource requirements, plus increasing development on low-lying coastal regions, floodplains and hill slopes that are well known to be vulnerable to storms.

Nearly all human societies and activities are sensitive to weather and climate. People have always adapted to weather extremes and climate variability, and many community coping strategies already exist. The Intergovernmental Panel on Climate Change (IPCC) *Special Report on Extreme Events*[6] acknowledges that there is not yet evidence of changes in the global frequency or intensity of hurricanes, droughts, floods or wildfires. The existence of a signature of human-caused global warming on sea level rise acceleration is still being debated. Nevertheless, the focus of analyses of adaptation to human caused climate change has been on anticipatory adaptation to new conditions that are outside of the range of those previously experienced, that are predicted in response to human-caused warming based on climate model simulations.

The extreme damages from recent hurricanes such as Katrina, Sandy and Harvey plus the recent billion dollar disasters from floods, droughts and wildfires, emphasize that the U.S. is highly vulnerable to current weather and climate disasters, not to mention the more extreme disasters that were encountered in the U.S. during the 1930's and 1950's. Possible scenarios of incremental worsening of weather and climate extremes over the course of the 21st century doesn't change the fundamental storyline that the U.S. is not well adapted to the current weather and climate variability, let alone the range that has been experienced over the past several centuries.

As a practical matter, adaptation has been driven by local crises associated with extreme weather and climate events, emphasizing the role of 'surprises' in shaping responses. Advocates of adaptation to climate change are not arguing for simply responding to events and changes after they occur; they are arguing for anticipatory adaptation. But arguments for preparing for the consequences of global warming rest on an implicit assumption that we can reliably anticipate the changes to which we will be adapting and therefore that we can sensibly plan for those changes. Unfortunately, climate models do not provide us with the information needed to anticipate the local consequences of climate variability and change.

The challenge for climate change adaptation is to work with a broad range of information about regional vulnerabilities and climate variability in the context of a decision-analytic framework that acknowledges deep uncertainty.

Resilience, anti-fragility and thrivability

In adapting to climate change, we need to acknowledge that we cannot know how the climate will evolve in the 21st century, we are certain to be surprised and we will make mistakes along the way. There is much to be learned from the extraordinary adaptations of species and ecosystems in the natural world.

[6] http://www.ipcc.ch/report/srex/

'Resilience' is the ability to 'bounce back' in the face of unexpected events. Resilience carries a connotation of returning to the original state as quickly as possible. Vulnerabilities to extreme events typically reveal a gap between the present situation and what is needed to reduce future vulnerability. Hence, we need to 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices.

The concept of 'thrivability' has been articulated by Jean Russell:[7]

> *"It isn't enough to repair the damage our progress has brought. It is also not enough to manage our risks and be more shock-resistant. Now is not only the time to course correct and be more resilient. It is a time to imagine what we can generate for the world. Not only can we work to minimize our footprint but we can also create positive handprints. It is time to strive for a world that thrives."*

A related concept is Nicholas Taleb's 'anti-fragility'[8] that focuses on approaches that enable us to thrive from high levels of volatility, particularly those unexpected extreme events. Taleb argues that the most profound and important of these unexpected events are by their very nature unpredictable. Taleb regards the real opportunity to be learning and growth from volatility and unexpected events – not to return to where you were, but to become even better as a result of encountering and overcoming challenges. Anti-fragile systems are dynamic rather than static, thriving and growing in new directions rather than simply maintaining the *status quo*. Anti-fragile systems require random events to strengthen and grow, and so avoid becoming brittle and fragile.

Strategies to increase anti-fragility include economic development, reducing the downside from volatility, developing a range of options, tinkering with small experiments, and developing and testing transformative ideas. Anti-fragility is consistent with decentralized models of policy innovation, that create flexibility and redundance in the face of volatility. This 'innovation dividend' is analogous to biodiversity in the natural world, enhancing resilience in the face of future shocks.[9]

A focus on policies that support resilience and anti-fragility avoids the uncertainties of attributing climate change to humans versus nature and avoids the hubris of thinking we can predict the future climate. The questions then become:

- How can we best promote the development of transformative ideas and technologies?
- How much resilience can we afford?

Decision – analytic approaches

Traditional approaches to risk management work well when the future is changing slowly, is predictable and doesn't generate much disagreement. Predict-then-act methods can backfire when uncertainties are underestimated, competing analyses engender disagreement and decision makers are blinded to surprises. Acting on forecasts of the unpredictable can contribute to bad decisions.

Climate-related decisions involve incomplete information from a fast-moving and irreducibly uncertain science. There are many different interests and values in play, the relevant time scales are

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[7] https://www.amazon.com/Thrivability-Breaking-through-World-Works/dp/1909470287
[8] Taleb, N 2012 *Antifragile: Things That Gain From Disorder*. Random House.
[9] Amanda Lynch, Climate Change Adaptation Policy Innovation: Subsidiarity, Diversity ad Redundancy. https://judithcurry.com/2014/02/14/uk-us-workshop-part-iii-strategies-for-robust-decision-making-for-climate-adaptation/

long and there is near certainty of surprise. Current policies often neglect known unknowns – leading to overconfidence and poor decisions.

The bottom-up resource-based vulnerability perspective[10] determines the major threats to local and regional water, food, energy, human health, and ecosystem function resources from extreme events including those from climate but also from other social and environmental issues. Relative risks can be compared with other risks in order to adopt optimal preferred mitigation/adaptation strategies. This is a more inclusive approach for policy makers to deal with the complexity of the spectrum of social and environmental extreme events that may occur, beyond just the focus on greenhouse gases as emphasized in the IPCC assessments.

Rather than seeking an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent. Flexible strategies can be quickly adjusted to advancing scientific insights and new conditions that arise. Robust decision making strategies[11] manage deep uncertainty by running the analysis backwards: start with a proposed strategy, identify future scenarios where strategy does and does not meet its goals, and identify steps that can be taken so strategy may succeed over a wider range of future scenarios. Stakeholders can then debate about how much robustness they can afford – which is more useful than debating what the future will be.

Climate Informed Decision Analysis (CIDA)[12] is an approach that identifies which scenarios of climate change would affect the project and then determines the likelihood of those scenarios. As a process committed to acceptance of deep uncertainties, CIDA does not attempt to reduce uncertainties or make predictions, but rather focuses on determining which decision options are robust to a range of plausible futures.

Adaptive governance[13] focuses on decentralized decision-making structures in the face of the complexity and uncertainty associated with rapid environmental change. This allows large, complex problem like global climate change to be factored into many smaller, more tractable problems. In an integral sense, addressing these smaller problems corresponds to adaptation to profound uncertainties that are inherent in complex systems that limit predictability. Planning to meet projected targets and timetables is secondary to continuing appraisal of incremental steps toward long-term goals. Each step in such trial-and-error processes depends on politics to balance and integrate the interests of multiple participants to advance their common interest.

The climate knowledge gap

The focus of the UN Framework Convention on Climate Change[14] on mitigation policies has arguably led the adaptation problem and its solutions in a direction that relies on mitigation-relevant science (i.e. attribution of global climate change and sensitivity to CO_2), rather than on understanding natural climate variability and regional risks in the context of vulnerability.

Climate models consistently indicate that the mean global temperature of the planet will rise with increasing CO_2 emissions. However, models show systematic errors in the simulated global mean temperature that is similar in magnitude to the size of the historical change we are seeking to

[10] https://pielkeclimatesci.files.wordpress.com/2012/10/r-3651.pdf
[11] https://www.rand.org/pubs/research_briefs/RB9701.html
[12] http://elibrary.worldbank.org/content/workingpaper/10.1596/1813-9450-6193
[13] http://press.uchicago.edu/ucp/books/book/distributed/A/bo8917780.html
[14] https://unfccc.int

understand.[15] Further, it is important to recognize that mean global climate is not what any one locale or nation will be adapting to.

There is a gap between the scale on which models produce consistent information and the scale that is relevant for human adaptation to climate change.[16] Attempts to 'downscale' the output of climate models are still in the early stages of development. Dynamical downscaling uses a higher-resolution regional model that is forced at the boundaries by outputs from the global climate models. The obvious problem with dynamical downscaling is that if the boundary conditions derived from the global climate model are in error, then these errors will propagate into the regional model.

Finally, existing climate models are unable to simulate realistically extreme outcomes such as a rapid disintegration of the West Antarctic Ice Sheet. Hence global climate models provide little relevant information regarding unlikely but potentially catastrophic impacts.

It is not at all obvious we will ever be able to model climate on scales that are quantitatively informative to adaptation decisions. Failure to appropriately communicate this 'weakest link' has been a critical failure of science-based policy-making.

Scenarios of 21st century climate variations and change

Adaptation strategies require information about future climate change, from both natural and human causes. Given the deep uncertainties surrounding regional climate change, a range of scenarios are needed in the context of robust decision making strategies.

The primary narrative for communicating climate change to decision makers has been as a gradual and predictable process, driven by emissions scenarios. This allegedly predictable signal is distinct from the unpredictable natural climate variability. Hence decision makers have focused on the apparently predictable trend associated with increasing emissions. However, to support decision making needs, all scientifically plausible scenarios need to be on the table, not just those selected by a particular heuristic, e.g. emissions scenarios.[17]

Natural climate variability refers to forcing from the sun, volcanic eruptions and natural internal variability associated with chaotic interactions between the atmosphere and ocean. The most familiar mode of natural internal variability is El Nino/La Nina. On longer multi-decadal time scales, there is a network of atmospheric and oceanic circulation regimes, including the Atlantic Multidecadal Oscillation and the Pacific Decadal Oscillation. It is these circulation regimes that dominate climate variability and extreme events on regional and decadal time scales.

20th century climate change is most often explained in terms of external forcing, with natural internal variability providing high frequency 'noise.' However, the role of large-scale multi-decadal ocean oscillations is increasingly understood to play a more fundamental role,[18] whereby the external forcing projects onto the modes of natural internal variability, producing 'shifts' in the climate system.[19] These circulation patterns act as a buffer on the climate system to small perturbations, but

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[15] https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2012MS000154

[16] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/2010/80-AdaptationtoGlobalWarming-2010.pdf

[17] https://www.researchgate.net/publication/305723870_Reconciling_anthropogenic_climate_change_and_variability_on_decadal_timescales

[18] https://www.nature.com/articles/19745

[19] Tsonis, A et al. 2007: A new dynamical mechanism for major climate shifts. *Geophys. Res. Lett.*, 34, L13705. https://pantherfile.uwm.edu/aatsonis/www/2007GL030288.pdf

over time can lead to an abrupt shift to a new state. These interactions on timescales from decades to centuries produce step changes in warming that integrate into a long-term complex trend. These complex interactions are a major determinant of changing climate risk, particularly with regards to extreme weather events and 'hot spots' of sea level rise.

Significant climate shifts in the past 50 years include:

- 1976/1977 Great Pacific Climate Shift: major shifts in atmospheric circulation patterns and extreme weather events, changes in the biota of the Pacific Ocean, greater frequency of El Nino events.[20]
- 1995 shift of the Atlantic Multidecadal Oscillation to the warm phase: shift to the active phase of Atlantic hurricanes, with a substantial increase in the number U.S. landfalls[21]
- 2001 synchronization of multiple climate modes: early 21st century 'hiatus' in warming[22]

The characterization of climate risk on regional and decadal time scales changes substantially if climate change is characterized as being gradual versus subject to shifts. Prediction of trends over decadal time scales may not be useful if the climate does not behave in a trend-like fashion. Of greater relevance for decision making is understanding the statistics of extreme events and potential future shifts in the climate.

For climate shifts, the main approach is no longer predicted trends based on global climate models, but rather a diagnostic approach based on the climate dynamics of the large-scale ocean circulation regimes. Step changes in climate can lead to significant changes in the frequency and magnitude of extremes and periodic shifts in means can be anticipated. A better understanding of how climate shifts, system complexity and systemic response may affect decision making should be a priority for developing scenarios of regional climate change.

Scenarios of global climate change

The scenarios of future global climate change provided by the IPCC AR5 are incomplete, focusing only on emissions scenarios and ignoring natural climate variations:

- *"With regard to solar forcing, the 1985–2005 solar cycle is repeated. Neither projections of future deviations from this solar cycle, nor future volcanic radiative forcing and their uncertainties are considered."* [IPCC AR5 WGI Section 12.2.3]
- *"Any climate projection is subject to sampling uncertainties that arise because of internal variability. [P]rediction of the amplitude or phase of some mode of variability that may be important on long time scales is not addressed."* [IPCC AR5 WGI Section 12.2.3]

Additional scenarios that should be considered for the trend of 21st century global climate change (individually or in combination):

- Scenario of volcanic activity matching the 19th century eruptions
- Grand solar minimum in the mid 21st century
- Shift to the cold phase of the Atlantic Multidecadal Oscillation (AMO)
- Lower values of climate sensitivity to carbon dioxide that are consistent with observationally-based energy budget analyses[23]

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[20] http://horizon.ucsd.edu/miller/download/climateshift/climate_shift.pdf
[21] https://www.researchgate.net/publication/235243382_The_Recent_Increase_in_Atlantic_Hurricane_Activity_Causes_and_Implication
[22] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2008GL037022
[23] Nicholas Lewis and Judith Curry, 2018: The impact of recent forcing and ocean heat uptake data on estimates of climate sensitivity. *Journal of Climate*, [https://doi.org/10.1175/JCLI-D-17-0667.1]

There are known structural inadequacies in global climate models (e.g. inadequate treatments of solar indirect effects, vertical ocean heat transfer and processes related to clouds). Hence in addition to sensitivity studies using climate models, semi-empirical methods should also be used in developing these additional scenarios.

Scenarios of regional climate change

Climate models are not the only, or best, way to generate future scenarios of regional climate change. Climate Informed Decision Analysis (CIDA) uses a broader range of climate scenarios[4]:

> *"Climate scenarios can be generated parametrically or stochastically to explore uncertainty in climate variables that affect the system of interest. This allows sampling changes in climate that include but are not constrained by the range of climate model projections. Scenarios can be developed as part of a stakeholder-driven, negotiated process, and climate projections can be used in this process. For scenarios in which the climate consequences exceed coping thresholds, it is then fruitful to evaluate the plausibility of the scenarios. Climate projections, paleoclimate reconstructions, and subjective climate knowledge could all inform such discussions."*

Several empirical strategies have been developed for providing scenarios of regional climate change:

- Pattern scaling: the main assumption is that the spatial pattern of change is assumed to remain constant at any time horizon or forcing scenario[24]
- Projections based on regional estimates of Transient Climate Sensitivity[25]
- Ensemble random analog prediction[26].

On decadal time scales, the greatest vulnerability is to extreme weather events such as floods, droughts, heat waves, heavy snowfalls and tropical cyclones. The future time series is of less relevance than decadal frequencies of extreme events (including clusters) and worst-case scenarios over the target time interval. Coarse-resolution global climate models do a poor job of simulating extreme weather events. A novel strategy has been proposed whereby high-resolution numerical weather prediction models are used in a hypothetical climate setting to provide tailored narratives for high-resolution simulations of high-impact weather in a future climate.[27]

My company Climate Forecast Applications Network (CFAN) has been developing a network-based dynamic climatology framework for developing regional decadal scenarios of future climate, focused on the decadal statistics of extreme weather events.[28] Central to this framework is the multi-decadal ocean oscillations, notably the Atlantic Multidecadal Oscillation (AMO), and Pacific Decadal Oscillation (PDO). These oscillations have a substantial impact on the frequency and intensity of tropical cyclones and on patterns of droughts and floods. The methodology for scenario generation includes generation of a synthetic climatology of the extreme events for each of the climate regimes as defined by the phase of ocean oscillations.

The greatest vulnerability is not to the smooth long-term changes but rather to the prospect by relatively rapid shifts in the climate or a clustering of extreme weather events in a particular location. The network-based scenario generation framework is ideally suited to incorporating projections of

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[24] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/2014/Robustness-of-pattern-scaled-climate-change-scenarios-for-adaptation-decision-support.pdf
[25] https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017GL076649
[26] http://www.lse.ac.uk/CATS/Assets/PDFs/Publications/Papers/1999-and-before/28-RandomAnalogueNonLinProcesses-1997-Paparella-etal.pdf
[27] https://www.nature.com/articles/nclimate2450
[28] https://docs.wixstatic.com/ugd/867d28_838be4ad291c4922857a0987685d635f.pdf

future climate shifts. Several recent efforts have focused on predicting the next shift in ocean circulation regimes, but this remains at the forefront of climate dynamics research.

Worst-case scenario

The worst-case scenario plays an important role in clarifying the upper bound of possible scenarios that would be genuinely catastrophic. The worst-case scenario is judged to be the most extreme scenario that cannot be falsified as impossible based upon our background knowledge.

It is estimated that fully melting Antarctica would contribute over 60 meters of sea level rise, and Greenland would contribute more than 7 meters, with an additional 1.5 meters of sea level rise from glaciers. How much of this is potentially realizable in the 21st century?

The IPCC AR5 predicted a likely range of sea level rise for the 21st century between 0.26 and 0.85 m (10 to 33 inches), depending on the emission scenario [Summary for Policy Makers]. This is compared to an observed sea level rise of 8 inches over the 20th century. Additional sea level rise of 1 or 2 feet over a century can be a relatively minor problem if it is managed appropriately. The primary concern over future sea level rise is related to the potential collapse of the West Antarctic Ice Sheet, which could cause global mean sea level to rise substantially above the IPCC's 'likely' range in the 21st century. The IPCC AR5 has medium confidence that this additional contribution from the West Antarctic ice sheet would not exceed several tenths of a meter of sea level rise during the 21st century [AR5 WG1 Chapter 13].

Subsequent to the 2013 IPCC AR5, there has been considerable focus on the worst-case scenario for global sea level rise. Strategies for generating the worst-case scenarios include process modeling that employs the worst-case estimate for each component, estimates from the deglaciation of the last ice age and the previous interglacial, and expert judgment.

Recent estimates of the worst-case scenario for global sea level rise in the 21st century range from 1.6 to 2.9 m (5 – 9.5 feet), with the recent NOAA Report[29] using a value of 2.5 m (8 feet). These values of sea level rise imply rates of sea level rise as high as 50 mm/yr by the end of the 21st century. For reference, the current global rate of sea level rise is about 3 mm/yr. Are these scenarios of sea level rise by 2100 plausible? Or even possible?

From the IPCC AR5:

> "*These high rates are sustainable only when the Earth is emerging from periods of extreme glaciation. During the transition of the last glacial maximum about 21,000 years ago to the present interglacial . . . coral reef deposits indicate that global sea level rose abruptly by 14 to 18 m in less than 500 years, in which the rate of sea level rise reached more than 40 mm/yr.*" [AR5 WG1 FAQ 5.2]

Rohling et al. (2013)[30] provide a geologic/paleoclimatic perspective on the worst-case scenario for 21st century sea level rise. These high projected rates of sea level rise are larger than the rates at the onset of the last deglaciation, even though today's global ice volume is only about a third of that at the onset of the last deglaciation. Starting from present-day conditions, such high rates of sea level rise would require unprecedented ice-loss mechanisms, such as collapse the West Antarctic Ice Sheet or activation of major East Antarctic Ice Sheet retreat.

[29] https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf
[30] https://www.nature.com/articles/srep03461

Can human caused global warming trigger such an extreme scenario on the time scale of the 21st century? While on the subject of worst-case scenarios of sea level rise, we should not ignore potential geologic 'wild cards'. In the more likely category of geologic impacts on the time scale of the 21st century is geothermal heat flux in the vicinity of the Greenland and Antarctic ice sheets.[31] The worst-case scenario of a collapse of the West Antarctic Ice Sheet seems more likely to be caused by a geological event than by greenhouse gas emissions. However, it is impossible to assign probabilities to such unprecedented wild card events, and they are regarded as extremely unlikely.

Sea level rise

Global mean sea level has increased by about 8-9 inches since 1880, with about 3 inches occurring since 1993. There is no question that local sea levels are increasing in some coastal regions at rates that are causing damage. However attributing sea level rise to human-caused global warming is very challenging. This is because there are much larger impacts on local sea level rise from regional ocean circulations, local geological processes, land use practices and coastal engineering. This challenge was recognized in the IPCC AR5 WGII Report:

- *[L]ocal sea level trends are also influenced by factors such as regional variability in ocean and atmospheric circulation, subsidence, isostatic adjustment, coastal erosion, and coastal modification. As a consequence, the detection of the impact of climate change in observed changes in regional sea level remains challenging.* [AR5 WG II Section18.3.3]

- *Anthropogenic causes of regional sea level rise include sediment consolidation from building loads, reduced sediment delivery to the coast, and extraction of subsurface resources such as gas, petroleum, and groundwater. Subsidence rates may also be sensitive to the rates of oil and gas removal. Regional sea level rise can exceed global mean sea level rise by an order of magnitude reaching more than 10 cm/yr.* [AR5 WG II Section5.3.2.2]

Sea level rise is one impact area where anticipatory adaptation strategies make sense; while there are substantial uncertainties about its magnitude, the sign of future sea level change is clearly positive.

Causes of regional sea level change

Sea levels have not been rising uniformly across the globe. One reason for the regional variations is dynamic redistribution of ocean mass via ocean circulations. Figure 1 shows that the Pacific Decadal Oscillation has resulted in recent sea level trends ranging from >10 mm/yr in the western Pacific to less than 1 mm/yr at several regions on the U.S. west coast [for reference, the global average value is ~ 3 mm/yr].

Short-term accelerations in sea level rise along the U.S. Atlantic coast have repeatedly occurred over the last century. These 'hot spots' can exceed rates of 4 inches in five years, and can occur anywhere along the U.S. Atlantic coast. A recent paper[32] argues that the North Atlantic Oscillation (NAO), a seesaw pattern in air pressure over different regions of the North Atlantic Ocean, could explain the shift in the position of short-term variations in sea level rise. Shifts in the NAO alter the position of

[31] A new volcanic province: an inventory of subglacial volcanoes in West Antarctica. Van Wyk, de Vries, Maximillian et al. Geological Society, London, Special Publications (2018)

[32] https://www.nature.com/articles/nature14491

the jet stream, wind patterns and storm tracks, all of which affect the distribution of water in the North Atlantic basin. The cumulative effects of NAO determine whether water will pile up to the north or south of Cape Hatteras. Thus, water piled up preferentially to the north of Cape Hatteras in the period 2009-2010, and to the south from 2011 to 2015.

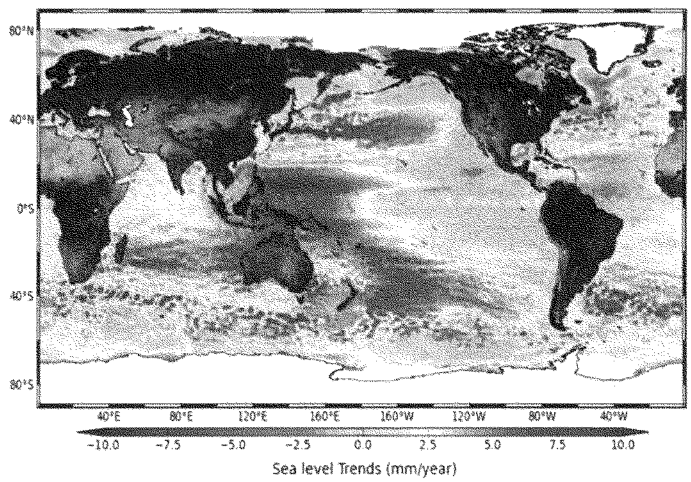

Figure 1. Satellite-derived rates of sea level rise over the period 1993-2015. Ablain et al. (2016) [33]

Glacial Isostatic Adjustment is the ongoing response of the solid Earth to land-ice shrinkage since the end of the last ice age. Melting glaciers and ice sheets and changes in land-water storage not only change ocean mass and thus global mean sea level, but also produce regionally distinct signatures from changes in the Earth's gravitational field and rotation, and lead to regional vertical land motion.

Vertical Land Motion can be a significant factor in the overall rate of local sea level rise. The highest rates of vertical land motion are found in regions of Louisiana (8–10 mm/year), Texas (4–7 mm/year) and along the Northeast Atlantic from Virginia to New Jersey (3–5 mm/year) (NOAA). In these regions, glacial isostatic adjustment and sediment compaction add about 0.5–2 mm/year to sea level change, and groundwater and oil/gas extraction processes further enhance local sea level rise. Land subsidence rates of 2–5 mm/year or more are not uncommon for the Northeast Atlantic and Gulf Coasts. For reference, global mean sea level rise is currently 3 mm/yr.

Local vulnerabilities and confounding factors

Observed and predicted rates of mean global sea level rise have little relevance for specific locations. There are numerous regional and local confounding factors that dominate local sea level rise, relative to the mean global rate. Examples are provided from some of the most vulnerable regions in the U.S.

[33] https://link.springer.com/article/10.1007/s10712-016-9389-8

Barrier islands are a type of dune system that forms by wave and tidal action parallel to the mainland coast. Barrier islands are prominent on the U.S. East Coast and Gulf Coast. The morphology of barrier islands is very dynamic. Storms and engineering practices that influence the natural flow of sediment have a substantial influence on this morphology, independent of sea level rise. Particularly for the barrier islands that have wealthy communities, aggressive engineering strategies are being developed. These most vulnerable islands are becoming laboratories for coastal sea level rise adaptation strategies. But it is futile to expect these changeable islands to remain as geologically stable entities for a very long times.

Isle de Jean Charles. Much ado has been made about the 'climate refugees' from Isle de Jean Charles off the coast of Louisiana, which is disappearing – in 1955, there were 22,000 acres while there are 320 acres today[34]. The principal problem traces back to the Great Mississippi Flood of 1927 when the U.S. Army Corps of Engineers responded by building giant levees to constrain the river, which stopped the flow of sediment into its delta. These refugees are more accurately referred to as 'Mississippi flood mitigation refugees.'

New Orleans. The issues of sea level rise and land loss in the Mississippi delta region are complex, with geological subsidence and the decline in sediment transported by the Mississippi river being the dominant drivers[35]. Since the 1950s, the suspended sediment load of the Mississippi River has decreased by ~50% due primarily to the construction of dams in the Mississippi basin. A new subsidence map of coastal Louisiana[36] finds the coastal region to be sinking at about one third of an inch per year (or 9 mm/yr) [for reference, the average rate of global mean sea level rise of 3 mm/yr]. For a city whose elevation averages one to two feet below sea level, sea level rise from human caused warming is not the dominant driver for the problems that New Orleans is facing. The Louisiana Coastal Protection and Restoration Authority, using funds from the British Petroleum oil spill settlement, is moving forward with two large sediment diversions. These diversions will start channeling huge volumes of river water in new directions, in a bid to protect areas around New Orleans in particular.[37]

Miami. Miami has a population of more than 5.5 million living at an elevation of 6 feet above sea level. Around 2011, the slow upward creep of the accelerated: from 2011 to 2015, the rate of sea level rise across the southeastern U.S. increased by a factor of six, from 3 mm/year to 20 mm/year, which was caused by a change in the NAO ocean circulation pattern. In South Florida, the main problem is drainage.[38] The systems here were designed to let storm water drain into the ocean when it rains. With sea levels now often higher than the exits to the run-off pipes, saltwater is instead running up through the system and into the streets. There is a growing recognition that at some point, certain areas in South Florida will no longer be viable places to live. The challenge is to ensure that the economy as a whole, including tourism, continues to thrive.

New York City. In New York City, sea level has risen 11 inches over the past century,[39] which is a greater rate than mean global sea level rise. It has been estimated[40] that land subsidence [sinking] in the New York City area has been roughly 3-4 inches per century. New York City is particularly

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[34] https://www.independent.co.uk/news/world/americas/time-almost-up-island-louisiana-sinking-into-the-sea-american-indians-coastal-erosion-isle-de-jean-a8280401.html
[35] https://www.sciencedirect.com/science/article/pii/S0025322716303553#bb0365
[36] https://phys.org/news/2017-06-highlights-louisiana-coast.html
[37] https://www.washingtonpost.com/news/energy-environment/wp/2018/04/11/seas-are-rising-too-fast-to-save-much-of-the-mississippi-delta-scientists-say/?utm_term=.dfa274d9c508
[38] http://www.bbc.com/future/story/20170403-miamis-fight-against-sea-level-rise
[39] https://tidesandcurrents.noaa.gov/sltrends/
[40] https://www.climate.gov/news-features/features/superstorm-sandy-and-sea-level-rise

vulnerable to the effects of sea level rise because it is built primarily on islands and has 520 miles of coastline. The City's waterfront is among its greatest assets. There is also substantial infrastructure and municipal facilities along the coast that are at risk from sea level rise, including roads, bridges, parks, waste transfer stations and wastewater treatment plants. Following Hurricane Sandy, a comprehensive plan has been developed: *City of New York: Building a Stronger, More Resilient New York.*[41] New York has developed a broad range of coastal protection measures that match the risks facing a given area: increase coastal edge elevations, minimize upland wave zones, infrastructure to protect against storm surge, improve coastal design and governance, restore estuaries wetlands, coastal nourishment, site elevation, and drainage systems.

San Francisco Bay area. Sea level has been measured in the San Francisco Bay area since the 19th century. Over the past the past 100 years, sea level has risen by 7.7 inches,[42] which is slightly lower than the global average rate. Landfill zones are sinking due to soil compaction, at a rate as much as one-half inch per year, threatening coastal infrastructure including the San Francisco International Airport. Another major contributor to sinking is groundwater pumping. Communities in the San Francisco Bay area have developed comprehensive plans to adapt to sea level rise.[43] Nevertheless, the San Francisco Bay Bridge ramp was recently built without any consideration of sea level rise. Less than two years after its completion, a report by the Metropolitan Transportation Commission finds that sea level rise is expected to permanently inundate several areas of the new span of the Bay Bridge and recommends a series of construction projects to protect the Bay Bridge, costing taxpayers an additional $17 million.[44]

At the 2017 *Conference on Regional Sea-level Changes and Coastal Impacts*, Kathleen White of the U.S. Army Corps of Engineers made the following statement:

> *"If we only look at the problem starting with just the climate signal, then it leads down a different path than if we look at components of sea level rise that are important to decision-makers."*[45]

Conclusions

Climate-related decisions involve incomplete information from fast-moving and irreducibly uncertain science. In responding to climate change, we need to acknowledge that we cannot know exactly how the climate will evolve in the 21st century, we are certain to be surprised and that we will make mistakes along the way.

Acting on forecasts of the unpredictable can contribute to bad decisions. Current policy making practices often neglect known unknowns – leading to overconfidence. Rather than negotiating an optimal policy based on a negotiated scientific consensus, robust and flexible policy strategies can be designed that account for uncertainty, ignorance and dissent. Flexible strategies can be quickly adjusted to advancing scientific insights and new conditions that arise.

[41] http://s-media.nyc.gov/agencies/sirr/SIRR_singles_Hi_res.pdf
[42] https://tidesandcurrents.noaa.gov/sltrends/
[43] http://sf-planning.org/sea-level-rise-action-plan
[44] https://blog.ucsusa.org/juliet-christian-smith/a-bridge-over-troubled-waters-how-the-bay-bridge-was-rebuilt-without-considering-climate-change?
[45] http://sciencedocbox.com/Geology/74213642-Conference-report-regional-sea-level-changes-and-coastal-impacts-july-2017-new-york-usa.html

On regional and decadal time scales, the greatest vulnerability to climate change is not associated with the smooth long-term warming trend but rather with rapid shifts in frequencies and intensities of extreme weather and climate events that are associated with natural internal climate variability. The challenge for climate change adaptation is to work with a broad range of information about regional climate variability and vulnerabilities in the context of a decision-analytic framework that acknowledges deep uncertainty and that we are almost certain to be surprised about future regional climate conditions and extreme weather events.

Rather than 'bouncing back' from extreme weather and climate events, we can 'bounce forward' to reduce future vulnerability by evolving our infrastructures, institutions and practices. A focus on policies that support resilience and anti-fragility avoids the hubris of thinking we can predict the future climate.

A regional focus on adapting to the risks of climate change allows for a range of bottom-up strategies to be integrated with other societal challenges, including growing population, environmental degradation, poorly planned land-use and over-exploitation of natural resources. Even if the threat from global warming turns out to be small, near-term benefits to the region can be realized in terms of reduced vulnerability to a broad range of threats, improved resource management, and improved environmental quality.

The focus on mitigation policies has led climate science in the direction that is targeted at attribution of global climate change and determining the sensitivity of climate to CO_2. There has been little focus on understanding natural internal climate variability and regional climate dynamics that is needed to inform adaptation to climate variability and change. A new emphasis of climate science on understanding natural climate variability and its regional impacts is needed to better understand our vulnerabilities to climate change in the 21st century.

Short Biography

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Dr. Judith Curry is President of Climate Forecast Applications Network (CFAN) and Professor Emerita of Earth and Atmospheric Sciences at the Georgia Institute of Technology. Dr. Curry received a Ph.D. in atmospheric science from the University of Chicago in 1982. Prior to joining the faculty at Georgia Tech, she held faculty positions at the University of Colorado, Penn State University and Purdue University. Dr. Curry's research interests span a range of topics in weather and climate. She has authored over 180 scientific papers, and is author of the textbooks *Thermodynamics of Atmospheres and Oceans* and *Thermodynamics, Kinetics and Microphysics of Clouds*. She is a prominent public spokesperson on issues associated with the integrity of climate science, and is proprietor the weblog Climate Etc. judithcurry.com. Dr. Curry has recently served on the NASA Advisory Council Earth Science Subcommittee, the DOE Biological and Environmental Research Advisory Committee, and the National Academies Climate Research Committee and the Space Studies Board and the NOAA Climate Working Group. Dr. Curry is a Fellow of the American Meteorological Society, the American Association for the Advancement of Science, and the American Geophysical Union.

Financial declaration

Funding sources for Curry's research have included NSF, NASA, NOAA, DOD and DOE. Recent contracts for CFAN include a NOAA contract to improve subseasonal weather forecasts, a DOE contract to develop extended range regional wind power forecasts and a DOD contract to predict extreme events associated with climate variability/change having implications for regional stability. CFAN clients include energy and power companies, reinsurance and asset management companies, other weather service providers, nongovernmental organizations and development banks.

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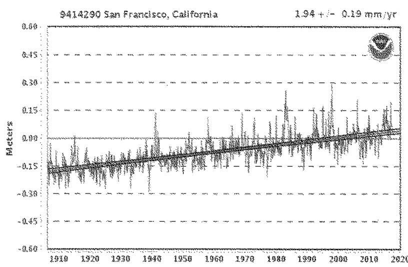

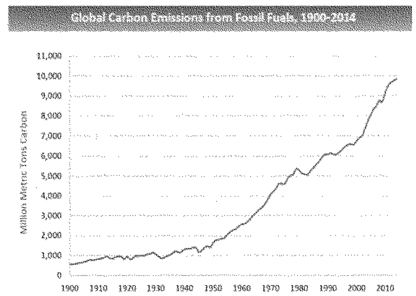

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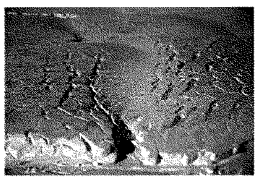
OPINION | COMMENTARY

The Sea Is Rising, but Not Because of Climate Change

There is nothing we can do about it, except to build dikes and sea walls a little bit higher.



Ice crevasses near the coast of West Antarctica. PHOTO: MARIO TAMA/GETTY IMAGES

By Fred Singer
May 15, 2018 6:27 p.m. ET

Of all known and imagined consequences of climate change, many people fear sea-level rise most. But efforts to determine what causes seas to rise are marred by poor data and disagreements about methodology. The noted oceanographer Walter Munk referred to sea-level rise as an "enigma"; it has also been called a riddle and a puzzle.

It is generally thought that sea-level rise accelerates mainly by thermal expansion of sea water, the so-called steric component. But by studying a very short time interval, it is possible to sidestep most of the complications, like "isostatic adjustment" of the shoreline (as continents rise after the overlying ice has melted) and "subsidence" of the shoreline (as ground water and minerals are extracted).

I chose to assess the sea-level trend from 1915-45, when a genuine, independently confirmed warming of approximately 0.5 degree Celsius occurred. I note particularly that sea-level rise is not affected by the warming; it continues at the same rate, 1.8 millimeters a year, according to a 1990 review by Andrew S. Trupin and John Wahr. I therefore conclude—contrary to the general wisdom—that the temperature of sea water has no direct effect on sea-level rise. That means neither does the atmospheric content of carbon dioxide.

This conclusion is worth highlighting: It shows that sea-level rise does not depend on the use of fossil fuels. The evidence should allay fear that the release of additional CO2 will increase sea-level rise.

But there is also good data showing sea levels are in fact rising at a constant rate. The trend has been measured by a network of tidal gauges, many of which have been collecting data for over a century.

The cause of the trend is a puzzle. Physics demands that water expand as its temperature increases. But to keep the rate of rise constant, as observed, expansion of sea water evidently must be offset by something else. What could that be? I conclude that it must be ice accumulation, through evaporation of ocean water, and subsequent precipitation turning into ice. Evidence suggests that accumulation of ice on the Antarctic continent has been offsetting the steric effect for at least several centuries.

It is difficult to explain why evaporation of seawater produces approximately 100% cancellation of expansion. My method of analysis considers two related physical phenomena: thermal expansion of water and evaporation of water molecules. But if evaporation offsets thermal expansion, the net effect is of course close to zero. What then is the real cause of sea-level rise of 1 to 2 millimeters a year?

Melting of glaciers and ice sheets adds water to the ocean and causes sea levels to rise. (Recall though that the melting of floating sea ice adds no water to the oceans, and hence does not affect the sea level.) After the rapid melting away of northern ice sheets, the slow melting of Antarctic ice at the periphery of the continent may be the main cause of current sea-level rise.

All this, because it is much warmer now than 12,000 years ago, at the end of the most recent glaciation. Yet there is little heat available in the Antarctic to support melting.

We can see melting happening right now at the Ross Ice Shelf of the West Antarctic Ice Sheet. Geologists have tracked Ross's slow disappearance, and glaciologist Robert Bindschadler predicts the ice shelf will melt completely within about 7,000 years, gradually raising the sea level as it goes.

Of course, a lot can happen in 7,000 years. The onset of a new glaciation could cause the sea level to stop rising. It could even fall 400 feet, to the level at the last glaciation maximum 18,000 years ago.

Currently, sea-level rise does not seem to depend on ocean temperature, and certainly not on CO2. We can expect the sea to continue rising at about the present rate for the foreseeable future. By 2100 the seas will rise another 6 inches or so—a far cry from Al Gore's alarming numbers. There is nothing we can do about rising sea levels in the meantime. We'd better build dikes and sea walls a little bit higher.

Mr. Singer is a professor emeritus of environmental science at the University of Virginia. He founded the Science and Environmental Policy Project and the Nongovernmental International Panel on Climate Change.

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Increased West Antarctic and unchanged East Antarctic ice discharge over the last 7 years

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Abstract. Ice discharge from large ice sheets plays a direct role in determining rates of sea-level rise. We map present-day Antarctic-wide surface velocities using Landsat 7 and 8 imagery spanning 2013–2015 and compare to earlier estimates derived from synthetic aperture radar, revealing heterogeneous changes in ice flow since ~ 2008. The new mapping provides complete coastal and inland coverage of ice velocity north of 82.4° S with a mean error of $< 10\,\mathrm{m\,yr^{-1}}$, resulting from multiple overlapping image pairs acquired during the daylight period. Using an optimized flux gate, ice discharge from Antarctica is 1929 ± 40 Gigatons per year ($\mathrm{Gt\,yr^{-1}}$) in 2015, an increase of $36 \pm 15\,\mathrm{Gt\,yr^{-1}}$ from the time of the radar mapping. Flow accelerations across the grounding lines of West Antarctica's Amundsen Sea Embayment, Getz Ice Shelf and Marguerite Bay on the western Antarctic Peninsula, account for 88 % of this increase. In contrast, glaciers draining the East Antarctic Ice Sheet have been remarkably constant over the period of observation. Including modeled rates of snow accumulation and basal melt, the Antarctic ice sheet lost ice at an average rate of $183 \pm 94\,\mathrm{Gt\,yr^{-1}}$ between 2008 and 2015. The modest increase in ice discharge over the past 7 years is contrasted by high rates of ice sheet mass loss and distinct spatial patters of elevation lowering. The West Antarctic Ice Sheet is experiencing high rates of mass loss and displays distinct patterns of elevation lowering that point to a dynamic imbalance. We find modest increase in ice discharge over the past 7 years, which suggests that the recent pattern of mass loss in Antarctica is part of a longer-term phase of enhanced glacier flow initiated in the decades leading up to the first continent-wide radar mapping of ice flow.

1 Introduction

The Antarctic ice sheet receives roughly 2000 Gt (~ 5.5 mm sea-level equivalent) of precipitation each year with > 90 % of this mass leaving as solid ice discharge to the ocean and the remaining < 10 % leaving in the form of sublimation, wind-driven snow transport, meltwater runoff and basal melt. Recent studies indicate significant mass loss from the Antarctic ice sheet that is likely accelerating (Harig and Simons, 2015; Helm et al., 2014; Martín-Español et al., 2016; McMillan et al., 2014; Rignot et al., 2011b; Shepherd et al., 2012; Velicogna, 2009). Understanding how this imbalance evolves is critical to providing meaningful projections of sea-level change. A major hurdle for improved attribution of mass changes determined from gravimetry and/or altimetry, and in determining mass changes themselves from the mass balance approach, is the difficulty in resolving continent-wide changes in ice discharge at high precision and accuracy for multiple epochs. This requires circum-Antarctic measurements of surface velocity on fine spatial scale and with sufficient accuracy ($\sim 10\,\mathrm{m\,yr^{-1}}$) to observe regionally coherent changes in flow.

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Earlier circum-Antarctic mappings of surface velocity have been based on synthetic aperture radar (SAR) data with incomplete coverage for 1996–2000 (Jezek et al., 2003; Rignot, 2006) and near-complete coverage for 2007–2009 (Rignot et al., 2011a). Applications of optical imagery for surface velocity mapping have heretofore been limited to more local scales (e.g., Bindschadler and Scambos, 1991; Scambos et al., 1992) due to limited sensor capabilities, cloudiness and too few repeat-image acquisitions. Improvements in sensor technology (particularly in radiometric resolution) and far higher image acquisition rates for Landsat 8, launched in 2013, largely overcome these limitations (Fahnestock et al., 2015; Jeong and Howat, 2015; Mouginot et al., 2017) and provide the ability to generate near-complete yearly mappings of surface velocity with high accuracy ($\sim 10\,\mathrm{m\,yr^{-1}}$).

Here we describe the application of two newly developed and independent feature tracking methodologies (JPL and NSIDC) that we applied to hundreds of thousands of Landsat image pairs covering the entire Antarctic ice sheet north of 82.4° S, producing six near-complete mappings of ice sheet surface velocities in both the 2013–2014 and 2014–2015 austral polar daylight periods. By differencing these velocity fields with the earlier SAR mapping (Rignot et al., 2011a) we resolve changes in ice surface velocity for the 7-year period between circa 2008 and 2015. Velocity changes are then used to estimate ice discharge on the basin scale and its change through time. For the determination of ice discharge we provide a novel approach to defining the cross-sectional area of ice flow (flux gate; Sect. 2.2) that greatly reduces uncertainties in estimates of ice discharge. By differencing estimates of ice discharge and basal melt rates (Van Liefferinge and Pattyn, 2013) from published estimates of the surface mass balance (van Wessem et al., 2016, 2014) we are able to estimate the net mass balance of the ice sheet on the basin scale, revealing recent patters of ice sheet imbalance.

2 Methods

2.1 Surface velocity

Glacier velocities were determined by feature tracking of matching path-row Landsat Collection 0 L1T and L1GT image pairs in the panchromatic Band 8 (15 m pixel size) using normalized cross correlation (NCC). To assess the sensitivity of our results to choices in Landsat processing methodology (e.g., search template size, spatial resolution, geolocation offset correction, data filtering, image-pair date separation and compositing) we examine multiple velocity mosaics derived from two independent processing methodologies developed by JPL and NSIDC (Fig. 1). Uncertainties in velocities were determined by comparing Landsat and SAR velocities measured at flux-gate nodes for basins with minimal change in ice discharge (basins B1–19 and B27), i.e., where velocity differences are assumed to be indicative measurement uncertainty. Uncertainties in velocities can be as high as 20–30 $\mathrm{m\,yr^{-1}}$ locally but are largely uncorrelated on basin scales (> 1000 km; see Appendix A for validation of the velocity fields). All velocity mosaics are freely downloadable from the NSIDC (National Snow and Ice Data Center). JPL and NSIDC processing chains share many of the same characteristics, with main differences being how the image-pair data are corrected for geolocation errors, how the imagery is searched for matching features and the choice of search parameters such as template size and spacing.

2.1.1 JPL auto-RIFT

Image-pair pixel offsets

The autonomous Repeat Image Feature Tracking (auto-RIFT v0.1) processing scheme was applied to all Landsat 7 and 8 images acquired between August 2013 and May 2016 with 80 % cloud cover or less. Images were preprocessed using a 5 by 5 Wallis operator to normalize for local variability in image radiance caused by shadows, topography and sun angle. All image pairs with less than 910-day separation were searched. Preprocessed image pairs were searched for matching features by finding local NCC maxima at subpixel resolution using Taylor refinement (Paragios et al., 2006) within a specified search distance. A sparse (1/16 of full search) NCC search was first used to determine areas of coherent correlation between image pairs. Results from the sparse search guide a dense search with search centers spaced such that there is no overlap between adjacent template search chips (i.e., the distance between template centers is equal to the template size). Highest-quality image pairs (< 20 % cloud and < 1-year separation) were searched using this approach, with a large search distance centered at zero pixel offset with a 32 by 32 pixel template chip. Spatially resolved statistics (mean and standard deviation of x and y displacements) are then used to guide a dense image search of all imagery with 16×16 or 32×32 pixel template chips depending on expected gradients in surface velocities. Areas of unsuccessful retrievals were searched with progressively increasing template chip sizes of 32, 64 and 128 that increase the signal to noise at the expense of spatial resolution.

Successful matches were identified using a novel normalized displacement coherence (NDC) filter. In this approach filtering is applied on search-normalized displacements, i.e., displacements divided by the NCC search distance. Normalized displacements are accepted if 7 or more of the values within a 5 by 5 pixel centered window are within one-quarter of a search distance for both x and y displacement components. This acceptance criterion is iterated on three times. Finally an iterative (two times) filter is applied to remove the few number of displacements that are retained by random agreement with neighbors. For this filter, displacements are compared to the centered 5 by 5 window median. Only values that agree within 4 times the centered 5 by 5 window

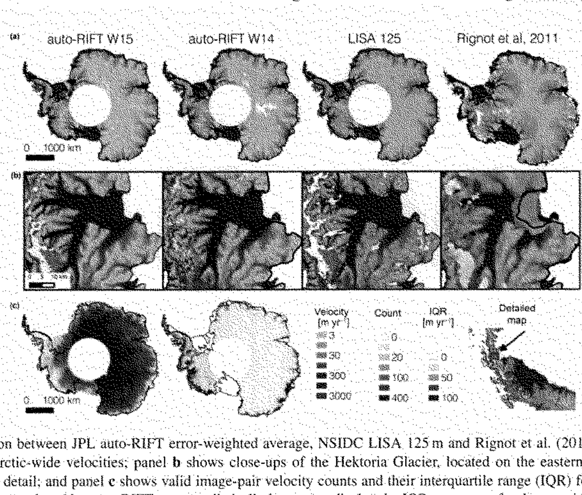

Figure 1. Comparison between JPL auto-RIFT error-weighted average, NSIDC LISA 125 m and Rignot et al. (2011a) surface velocities. Panel **a** shows Antarctic-wide velocities; panel **b** shows close-ups of the Hektoria Glacier, located on the eastern side of the Antarctic Peninsula for spatial detail; and panel **c** shows valid image-pair velocity counts and their interquartile range (IQR) for the auto-RIFT W15 mosaic. Formal errors produced by auto-RIFT are unrealistically low so we display the IQR as a proxy for the per-pixel random error.

mean absolute deviation are retained. The NDC filtering approach is highly generic and very effective at removing random image-pair matches but not at removing match blunders that can result in spatially coherent errors. Remaining blunders are filtered during the merging process using information from all image pairs.

Image-pair pixel displacements were calculated from georeferenced images that are in Antarctic Polar Stereographic (EPSG 3031) projection. This introduces scale distortions that increase with distance from the latitude of origin (71° S). We corrected for this scale distortion when converting from pixel displacement to velocity following the equations presented in Snyder (1987).

Image geometry between image pairs is highly stable, but images suffer from large x and y geolocation errors (~ 15 m). This resulted in good gradients in velocity but poor absolute velocity. Displacement fields were also contaminated by match blunders (e.g., matching along shadow edges or of surfaces obscured by cloud in one of the two images). Therefore, displacement fields required heavy post-processing to isolate the geophysical signal. This was done by stacking all time-normalized displacements (velocities), co-registering them over stationary or slow flowing surfaces and filtering based on the interquartile range (IQR) determined for each pixel of the displacement stack. All x and y displacements that fell outside of the range $Q_1 - T \times \mathrm{IQR}$ to $Q_3 + T \times \mathrm{IQR}$ were culled from the data set, where Q_1 and Q_3 are the first and third quartile, respectively, and T is a scalar that defines the acceptance threshold.

Reference velocity

A reference velocity (Vx_0, Vy_0) field was generated from all individual image-pair velocities. As a first step, gross outliers were removed from the unregistered data by setting T equal to 3. Stacked displacement fields were then coregistered by iteratively correcting for the median x and y velocity difference between individual image-pair velocities and static reference velocity fields (Vx_{ref} and Vy_{ref}) over stationary or slow flowing surfaces, stopping after five iterations. For each iteration, coregistered displacements were filtered setting T equal to 1.5, and the effective template chip size (resolution of the velocity field) was coarsened for low-velocity gradients ($< 10\,\mathrm{m\,yr^{-1}}$ between adjacent search chips) to minimize high-frequency noise while retaining spatial gradients.

Initial Vx_{ref} and Vy_{ref} were defined as all grounded ice pixels with median velocities $< 10\,\mathrm{m\,yr^{-1}}$ and with > 100 valid retrievals. Where these conditions were not met, Vx_{ref} and Vy_{ref} were supplemented with Rignot et al. (2011a) velocities $< 10\,\mathrm{m\,yr^{-1}}$. Additionally, all pixels containing exposed rock were initially assigned a Vx_{ref} and Vy_{ref} of $0\,\mathrm{m\,yr^{-1}}$. Exposed rock was identified using the SCAR Antarctic Digital Database (Thomson and Cooper, 1993; Fig. 2). The initial template chip size was set to the minimum chip size for which 40 % of the valid displacements in the stack were determined using a chip of that size or smaller. After each coregistration of the data, Vx_{ref} and Vy_{ref} were set equal to the error-weighted velocity for those pixels that have velocities $< 50\,\mathrm{m\,yr^{-1}}$ and a Vx and Vy

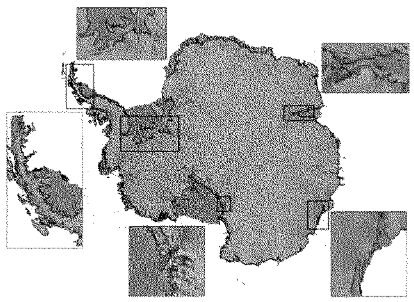

Figure 2. Antarctic ice sheet velocities overlain on the MODIS Mosaic of Antarctica (Scambos et al., 2007). Areas of imposed zero change in velocity are shown in cyan. Areas of prescribed zero surface velocity (rock outcrops) are shown in red as defined according to the Antarctic Digital Database (http://www.add.scar.org).

IQR < 40 m yr^{-1}. All pixels containing exposed rock are reassigned a Vx_{ref} and Vy_{ref} of 0 m yr^{-1}. The uncertainty of each image-pair velocity field was determined as the standard deviation of the residuals to Vx_{ref} and Vy_{ref}. When there were fewer than 320 coregistration pixels within an image pair, the uncertainty was set to the RSS (root of sum of squares) of the pointing uncertainty of each image.

JPL auto-RIFT annual fields

All image-pair velocities for a given year Y (center date of image pair > 15 July, $Y - 1$ and < 15 July Y) were coregistered using the reference velocity field (Vx_0, Vy_0), where Vx_{ref} and Vy_{ref} were set equal to the error-weighted velocity (Vx_0, Vy_0) for those pixels that have velocities < 50 m yr^{-1} and Vx_0 and Vy_0 IQR < 40 m yr^{-1}. Annual error-weighted averages and median velocities were first calculated setting the filter limits based on the quartile ranges of Vx_0 and Vy_0 and setting $T = 3$. Velocities were further refined by setting the filter limits based on the quartile ranges of initial annual values and using a more stringent acceptance threshold of $T = 1.5$.

Using this approach we calculated four nearly complete Landsat 8 velocity maps: median (M) and error-weighted average (W) velocities for years 2014 and 2015. The 2014 and 2015 velocities were derived from ~ 100 000 and ~ 200 000 unique image pairs, respectively (Fig. 1).

2.1.2 NSIDC LISA

NSIDC's Landsat ice speed for Antarctica processing (LISA v1.0) used the Python image correlation, PyCorr v1.10, described in detail by Fahnestock et al. (2015). PyCorr was applied to Landsat 8 data separated by 16 to 400 days, spanning 26 September 2013 to 1 April 2015 using a reference template size of 300 × 300 m with 300 m spacing between search templates. Images were manually selected based on the proportion of cloud-free surface coverage from the group of images with less than 70 % cloud cover. A high-pass filter of approximately 250 m spatial scale was applied to the images to enhance surface detail and suppress topographic shading.

PyCorr outputs a quality metric delcorr, which is the difference between the regression coefficient of the peak match and the second-highest match outside of a 3 × 3 cell area around the peak. All displacement values with a delcorr value less than 0.15 were eliminated. Velocities are further filtered by examining the difference between the velocities at the assessed pixel with the eight surrounding values. Velocities with no neighbors were masked. Velocities with one neighbor were masked when the absolute difference between the two values was greater than 365 m yr^{-1}. Velocities with two neighbors were masked if they exceeded 3 standard deviations of the mean. Finally the standard deviation of each 3 × 3 region was computed, and the center pixel of each region was masked when the corresponding standard deviation is greater than 365 m yr^{-1}.

Image-pair geolocation errors were corrected using three sets of x–y velocity offsets. Each set of offsets were computed over rock (http://www.add.scar.org) and near-zero ice (< 20 m yr^{-1}) and low ice velocity (< 40 and > 20 m yr^{-1}) areas according to Rignot et al. (2011a). Offset corrections were then weighted by count and applied to individual image-pair results.

Resulting velocities for each image pair were bilinearly resampled to the target grid spacing of either 750 or 125 m. These grids were then composited using a weighting scheme that favors the more accurate long-interval velocity determinations (16-day pairs, 0.3 weighting; 32-day pairs, 0.6; 48-day pairs, 0.9; > 48-day pairs, 1.0). Additionally, a weighting factor was applied to each cell based on the mean NCC and delcorr values. Mosaics were then corrected for projection scale distortion, stacked and combined in a weighted average scheme. The number of image pairs in the LISA v1.0 grid ranges from ~ 10 to over 200 (Fig. 1).

2.2 Flux gates

Estimation of ice flux from measurements of surface velocity requires knowledge of the vertical density profile, flow cross-sectional area (flux gate) and an assumption of the relationship between surface and depth-averaged velocity. The most accurate estimates of ice thickness come from radio-echo-sounding (RES) measurements, but RES data only exist for about 19 % of the ice sheet grounding line. For the calculation of discharge, we choose to compromise proximity to the grounding line for inclusion of more upstream RES data and for avoiding glacier shear zones with poorly constrained

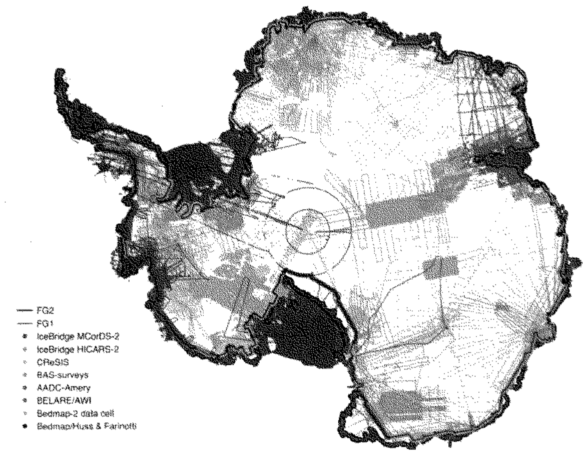

Figure 3. Radio-echo-sounding data used to compile flux gates FG1 and FG2. An overview of data used and their references is provided in Table 1.

Table 1. Data sources and percentages for radio-echo-sounding data used to compile flux gates.

Data set	GL0	FG1	FG2	Reference
IceBridge MCoRDS-2	5.3 %	16.1 %	31.5 %	Leuschen et al. (2010)
IceBridge HiCARS-2	2.1 %	5.4 %	20.2 %	Blankenship et al. (2012)
CReSIS	0.4 %	0.3 %	0.3 %	Gogineni (2012)
BAS surveys	1.7 %	7.4 %	9.0 %	https://legacy.bas.ac.uk/data/aerogeo/
AADC Amery	2.6 %	2.5 %	12.1 %	Allison and Hylland (2010)
BELARE/AWI	0.1 %	2.4 %	4.1 %	Callens et al. (2014, 2015)
Bedmap-2 data cell	6.9 %	8.3 %	18.3 %	Fretwell et al. (2013)
Sum	19.2 %	42.4 %	95.6 %	

velocities. We do so by modifying the best-known grounding line to go inland of major shear zones and to follow nearby RES flight lines from which valid ice thickness data can be extracted. We prioritize the nearest and most recent RES data available from seven freely available data sets (Fig. 3 and Table 1). For flux gates with no RES data within 1 km distance, ice thickness values are extracted by bilinear interpolation from the ice thickness grid of Huss and Farinotti (2014) over the Antarctic Peninsula and Bedmap-2 (Fretwell et al., 2013) for the rest of Antarctica. We generate three alternative flux gates: a grounding-line flux gate (GL0) based on a synthesis of mappings of the grounding line, a lightly modified version of GL0 improved by following RES profiles upstream and in close proximity to the grounding line (FG1) and a flux-gate outline based solely on RES profiles in favorable positions for calculating flux (FG2).

GL0 is a best-assessment grounding-line position from a synthesis of incomplete data first presented in Depoorter et al. (2013) that has been updated here by more recent grounding-line mappings in the Amundsen Sea region (Rignot et al., 2014, 2011b) and for the Totten Glacier in East Antarctica (Li et al., 2015; Rignot et al., 2013); two highly dynamic regions with considerable ice fluxes and changes in grounding-line position. Ice thickness was mainly extracted from the gridded products of Bedmap-2 (67 %) and the Antarctic Peninsula (9 %), but also a considerable amount of RES data that were within 1 km (applied threshold) of the grounding line (19 %). For that, we also considered grid cells in Bedmap-2 that have been derived directly from RES data

(7 %), as indicated in a data coverage mask. These thickness values have a much lower uncertainty (mean 68 m) than the interpolated thicknesses in areas not covered by RES (mean 168 m).

FG1 is a modified version of GL0 that follows RES flight lines (Fig. 3) or Bedmap-2 data cells that are in the vicinity of the grounding line. Whether or not to divert from the grounding line in favor of RES profiles was determined ad hoc rather than applying a strict distance threshold. Long, continuous RES profiles further apart were more likely to be followed than short, scattered RES data closer to the grounding line. In general, the modified parts of FG1 are within a few tens of kilometers from the GL0 and even less so in the Amundsen and Bellingshausen Sea coasts and the Filchner-Ronne ice shelf regions, where RES flight lines are often aligned with the grounding line. Almost all of these important regions are covered by RES data in FG1, and for Antarctica as a whole the RES coverage is 42 % (Table 1). We found that FG1 was the most suitable flux-gate line for estimating changes in ice discharge due to its close proximity to the grounding line and high coverage of RES data.

FG2 is a modified version of FG1 that further prioritizes RES flight lines over proximity to the grounding line around the entire continent. Only slight modifications were made in regions like the Amundsen and Bellingshausen Sea coasts, the Filchner-Ronne ice shelf and Dronning Maud Land for which many near-grounding-line RES data exist, but for parts of East Antarctica and along the Transantarctic Mountains the modification can be several hundred kilometers (Fig. 3). The total coverage of RES data along FG2 is 96 % (Table 1). We used this flux-gate line to estimate absolute discharge for the ice sheet, but not for assessing temporal changes in discharge, because they are often most pronounced near the grounding line that is better sampled by FG1.

The average point spacing along the three flux-gate lines is 198–265 m, with a maximum spacing of 400 m to ensure sufficiently dense sampling of ice thickness and surface velocity for ice flux calculations (see Sect. 2.3 for a detailed discussion of resolution-dependent errors in flux calculations). Flux-gate points without RES data and within the rock mask of the SCAR Antarctic Digital Database (< 4 %; Thomson and Cooper, 1993; Fig. 2) were assigned a zero ice thickness. Since the thickness data were provided as physical ice thicknesses, we subtracted modeled average (1979–2015) firn air content (FAC; see Sect. 2.5) to obtain ice-equivalent thicknesses, assuming ice has a density of $917\,\mathrm{kg\,m^{-3}}$, relevant for ice flux calculations.

For further analyses, we also extracted point attributes for source data and year, surface elevation, FAC and all available thickness data. Histograms of ice thickness, uncertainties in ice thickness, date of thickness measurement, FAC, uncertainty in FAC, surface velocity, ice thickness change rate and uncertainty ice thickness change rate for all three flux gates are shown in Fig. 4. Flux gates and extracted ancillary data are available from the National Snow and Ice Data Center.

2.3 Ice discharge

We calculate ice flux (F) by multiplying the x and y velocity component (Vx/y) by the width of the flux gate projected in the x and y coordinates (Wx/y) and ice-equivalent thickness (H) at each flux node (i) and summing

$$F = \sum_{i=1}^{nn} (Vx_i Wx_i + Vy_i Wy_i) H_i, \qquad (1)$$

where nn is the number of nodes at which ice flux is calculated. Here we defined the flux gate following polygon convention with the upstream side of the flux gate being defined as to the right-hand side of the polygon gate vector as one moves from node n to node $n+1$. In this convention Wx is negative when $y_{n+1} > y_n$ and Wy is negative when $x_{n+1} < x_n$. Ice discharge (D) at the grounding line of the ice sheet corresponds to F for the GL0 flux gate. Applying mass conserving principles (Morlighem et al., 2011), D is equal to $F + \mathrm{SMB} + \mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t$ for the FG1 and FG2 flux gates. SMB is the unmeasured flux due to a positive surface mass budget of the area between the flux gate and the grounding line and is estimated from RACMO2.3 climatology (1979–2015; see Sect. 2.4). SMB is corrected (reduced) for basal melt occurring between the flux gate and the grounding line which does not contribute to solid ice discharge (Van Liefferinge and Pattyn, 2013). $\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t$ is the unmeasured flux due to ice flow convergence and divergence between the flux gate and the grounding line, which we refer to as the dynamic volume change. This is accounted for by assuming that firn corrected CryoSat-2 elevation change rates (Sect. 2.6) measured over ice moving at $> 200\,\mathrm{m\,yr^{-1}}$ that lies between the flux-gate and the grounding line can be attributed to dynamic volume change. Rates of volume change in 2008 and 2015 were extrapolated using the measured acceleration in the rate of elevation change over the period of CryoSat-2 data (2011–2015). Measured dynamic volume loss is considered to increase total discharge and vice versa. Uncertainty in the dynamic volume change can not be rigorously quantified and are therefore conservatively assumed to be $0.1\,\mathrm{m\,yr^{-1}}$ times the area between the grounding line and the flux gate having a surface velocity $> 200\,\mathrm{m\,yr^{-1}}$ or 30 % of the magnitude of the estimated dynamic volume change, whichever is larger. A velocity cutoff of $200\,\mathrm{m\,yr^{-1}}$ was selected to separate volume changes resulting from changes surface mass balance and those resulting from changes in dynamics. This threshold is arbitrary. Even so, the dynamic volume change correction is very small and insensitive to the selected cutoff velocity.

Calculation of discharge is highly sensitive to the definition of the flux gate and to any vertical gradient in the ice flow (Chuter et al., 2017; Mouginot et al., 2014; Rignot, 2006; Rignot and Thomas, 2002). When calculating ice flux, we assume that there are no vertical gradients in ice velocity. This assumption introduces a small positive bias (< 0.4 %) but is negligible relative to other sources of error.

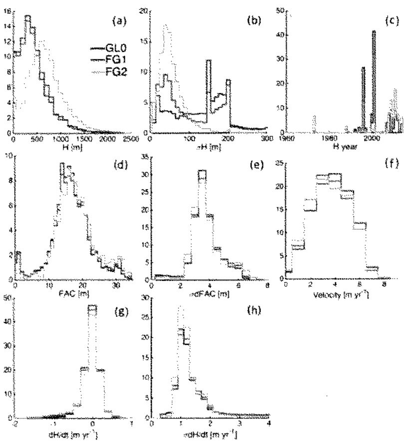

Figure 4. Histograms of ice-equivalent thickness **(a)**, uncertainty in ice-equivalent thickness **(b)**, year of ice thickness measurement **(c)**, firn air content **(d)**, uncertainty in firn air content **(e)**, surface velocity **(f)**, change rate of ice-equivalent thickness **(g)** and uncertainty in change rate of ice-equivalent thickness **(h)** for GL0, FG1 and FG2 flux gates. The y axis is the percentage of flux nodes that fall within each histogram bin.

See Appendix A for the calculation of the expected vertical gradient in ice velocity. One known issue is the systematic underestimation of ice flux with the coarsening of the resolution of the basal topography and/or the surface velocity (Fig. 5). This happens because fast-moving ice is concentrated in basal troughs: higher velocities multiplied by larger ice thickness and lower velocities multiplied by smaller ice thickness do not equate to average thickness multiplied by average velocity. FG2, which follows high-resolution RES profiles around almost the entire continent at the expense of proximity to the grounding line, provides the cross-sectional area with the lowest uncertainty and is most appropriate for estimating the total discharge, even after having to account for additional mass input between the gate and the grounding line. FG1 strikes a balance between proximity to the grounding line (GL0) and the distance from ice thickness observations. This gate is best suited for estimating changes in ice discharge. Our best estimate of total discharge is computed using the 2015 error-weighted average auto-RIFT velocities, FG2 and an estimate of additional mass flux between FG2 and GL0. We then compute the change in discharge between the 2015 and 2008 period at FG1 and subtract this from our best estimate of total discharge, accounting for dynamic volume change and changes in ice thickness between periods.

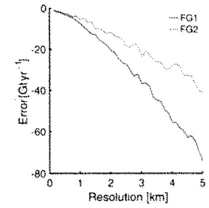

Figure 5. Error in total Antarctic discharge (relative to best estimate) when velocity and ice thickness are averaged for increasing along-flux-gate resolutions prior to computing flux.

This multi-flux-gate approach greatly reduces errors in estimates of ice discharge.

For areas south of the Landsat observation limit, we first calculate the total flux across gates located $> 82.4°$ S using the 1997 and 2009 SAR velocity mappings of Scheuchl et al. (2012). To determine a representative 2015 flux rate we extrapolate the 2009 estimate assuming the same rate of change in discharge as observed for the 1997–2009 period.

Changes in flux ($\mathrm{d}F$) were calculated at all flux-gate nodes (i) where both velocity mappings were valid and assumed to be unchanged elsewhere. In our analysis of velocities we found that there were some geocoding issues between the SAR (Rignot et al., 2011a) and Landsat velocities, which are most likely due to errors in the elevation model used to convert from radar slant range coordinates to a location on the Earth surface. We also found the SAR velocities unreliable for most of the northwest Antarctic Peninsula, where velocities near the grounding lines of narrow outlet glaciers were unrealistically low and likely the results of interpolation to areas of missing data. To minimize the impact of these artifacts in our flux-change analyses, we prescribed areas of zero change in flux along shear margins where changes are expected to be small and for much of the northwest Antarctic Peninsula (Fig. 2). Any residual geocoding errors are expected to introduce noise into our analysis but are unlikely to significantly bias our estimates of flux or flux change as errors will somewhat cancel when integrated across the entire glacier cross section (errors are typically of similar magnitude but opposite sign along right and left flow margins). See Appendix A for a comprehensive discussion of the uncertainty quantification.

One known limitation of our analysis is that the SAR velocity mosaic (Rignot et al., 2011a) that we difference our Landsat velocities with is derived from data spanning the period 1996–2009 with no information provided on the effective date of the data. We assume that the SAR mosaic has a representative date of circa 2008 as most data used in the mosaic was collected between 2007 and 2009. This data has been used previously to estimate total Antarctic discharge in Rignot et al. (2013) with a reference date of 2007 to 2008 and in Depoorter et al. (2013) with a reference date of 2007 to 2009. Individual year composites of the data used in older mosaic were recently made available (Mouginot et al., 2017). These new data come with more precise time stamps but at the expense of reduced horizontal resolution (1 km vs. 450 m), reduced spatial coverage and larger uncertainties. To ensure that our stated time period of circa 2008 is appropriate we resample (linear interpolation) the original SAR velocity mosaic to 1 km and compare to the error averaged 2007–2008 and 2008–2009 velocities from the new data set. Differences in flux across the FG1 are less than $2\,\mathrm{Gt\,yr^{-1}}$ for all basins except for basins 12, 13, 14 and 24 that differ by −4, −5, −6 and $4\,\mathrm{Gt\,yr^{-1}}$, respectively. Some of the difference can be attributed to real differences in flow but also from differences in uncertainties between products (the original SAR mosaic having lower errors, particularly for the East Antarctic) and from differences in horizontal resolution. From this analysis we concluded that the best estimate of flux for the ~ 2008 period is produced by the earlier mosaic that has higher spatial resolution and the lower uncertainty, which is derived from the same underlying data contained in the annual mosaics. We also determine the period "circa 2008" characterizes well the effective date of the earlier SAR mosaic.

2.4 Surface mass budget

Here we estimate SMB for the 2008–2015 period from Regional Atmospheric Climate Model version 2.3 (RACMO2.3) output at a horizontal resolution of 5.5 km for the Antarctic Peninsula (van Wessem et al., 2016) and 27 km elsewhere (van Wessem et al., 2014). In RACMO2.3, SMB is calculated as the total precipitation (from snow and rain) minus total sublimation (directly from the surface and from drifting snow), wind-driven snow erosion and meltwater runoff. For the six Antarctic Peninsula basins (B1, B23–27), entirely or partially covered by the high-resolution model, we use the 27 km model output for the missing years of 2014 and 2015. For these basins, the 27 km model output was scaled to better agree with the 5.5 km output using the delta scaling approach. Uncertainty in SMB is taken to be 20 % and is treated as uncorrelated between basins. The reader is referred to the works of van Wessem et al. (2014 and 2016) for a thorough discussion of the model setup, model validation and SMB uncertainties.

2.5 Firn air content

To convert volume fluxes to mass fluxes, the depth-averaged ice-sheet density is needed. FAC is a measure of the residual column that would remain if the firn column were compressed to the density of glacier ice, assumed to be $917\,\mathrm{kg\,m^{-3}}$. We estimate FAC using the firn densification model IMAU-FDM (Ligtenberg et al., 2011, 2014). IMAU-FDM simulates firn densification by dry compaction and through meltwater processes (percolation, retention and refreezing) and is forced at the surface by 3-hourly resolution output of RACMO2.3 (van Wessem et al., 2016, 2014): surface temperature, 10 m wind speed, precipitation (solid and liquid), sublimation, wind-driven snow erosion/deposition and surface melt. The simulation over the entire Antarctic continent (at 27 km grid resolution) covers 1979–2015, while the Antarctic Peninsula simulation (at 5.5 km grid resolution) only covers 1979–2013. Both simulations output FAC at 2-day temporal resolution. The IMAU-FDM is calibrated using 48 depth–density observations from across Antarctica (Ligtenberg et al., 2011), and results have been successfully used to convert satellite altimetry (e.g., Gardner et al., 2013; Scambos et al., 2014; Shepherd et al., 2012) and ice thickness measurements (e.g., Depoorter et al., 2013; Fretwell et al., 2013) into estimates of ice mass change and ice-equivalent thickness. Although time-evolving FAC is simulated throughout 1979–2015, we use the climatological average FAC as the most robust correction of our flux-gate thicknesses that are based on source data from many different times, sometimes unknown.

Uncertainties in the simulated FAC originate from either the observations used in the IMAU-FDM calibration process or the RACMO2.3 forcing data. This has been quantified at 10 % (Supplement of Depoorter et al., 2013), composed of measurements errors in the observations of the pinning points in a depth–density profile: surface density, depth of $550\,\mathrm{kg\,m^{-3}}$ level and depth of $830\,\mathrm{kg\,m^{-3}}$ level. The RACMO2.3 uncertainty is primarily caused by the assumption used for model initialization; to initialize the IMAU-FDM, it is assumed that the climate over the past 100–1000 years was equal to the 1979–2013/15 average climate (Ligtenberg et al., 2011). Therefore, errors in the climatic forcing during the initialization period have a direct effect on the simulated firn density profile and subsequent FAC. Using sensitivity simulations, it was found that a 1 % perturbation in accumulation during the initialization period causes a 0.75 % error in FAC. Similarly, a 1 % perturbation in the melt / accumulation ratio results in a 0.27 m error in FAC. The melt / accumulation ratio was used instead of the total melt, as the amount of annual snow that melts away in summer (i.e., the ratio between annual melt and annual accumulation) mainly determines how much firn pore space remains rather than the total amount of melt.

Along the ice-sheet grounding line the mean and standard deviation of FAC are 16.3 ± 6.1 m with associated uncertainties of 3.7 ± 1.0 m. The combined uncertainties of the firn observations and the RACMO2.3 forcing of accumulation and surface melt showed the highest uncertainties on the western side of the Antarctic Peninsula, where high accumulation is combined with high melt. In areas where the modeled FAC uncertainty was higher than the actual FAC, the uncertainty was re-set to the same value as the FAC.

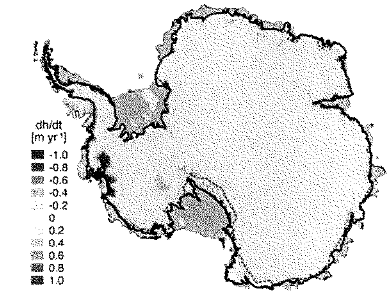

Figure 6. Surface elevation change for the period 2011 to 2015. Flux gate FG2 shown with blue dashed line and GL0 shown with heavy black line.

2.6 Surface elevation and elevation change

To account for thickness changes between the times of discharge calculation (2008 and 2015) and to correct for dynamic volume change between the flux gate and the grounding line, we use surface elevation rates estimated from CryoSat-2 radar altimetry between January 2011 and January 2015 (Fig. 6). CryoSat-2 elevations were derived from the ESA L1c product using the methodology developed by Nilsson et al. (2016). For each CryoSat-2 observation mode (LARM and SARIn), the derived surface elevations were separated into grounded and floating ice using the grounded and floating ice definitions from Depoorter et al. (2013) gridded to a 240 m in stereographic (EPSG: 3031) projection. Geophysical range corrections were applied to all data according to Bouzinac (2015). For floating ice, the tidal corrections (ocean tide and ocean loading) were replaced with values generated from the CATS2008 tidal model (Padman et al., 2008).

Surface elevation changes and rates of acceleration were generated using the surface fit method, described in Nilsson et al. (2016), onto a 1 km polar-stereographic grid (EPSG: 3031) for each mode. The derived elevation change distribution was edited to remove solutions with a magnitude larger than $\pm 15\,\mathrm{m\,yr^{-1}}$, similar to the approach taken by Wouters et al. (2015). The edited data was then interpolated onto a 1 km grid using the weighted average of the 16 closest grid points, weighted by their standard error from the least-squares solution and distance. The standard error of the rate of change is assumed to be indicative of the formal error of each measurement. No correction for potential trends in FAC and glacial isostatic adjustment are applied, which may cause surface elevation rates to deviate from ice-equivalent thickness rates.

2.7 Mass budget

To assess the net ice sheet mass budget during the 2008–2015 period, we combine our new estimates of discharge (Sect. 2.3) with estimates of surface mass budget (Sect. 2.4) and basal melt rates (Pattyn, 2010; Van Liefferinge and Pattyn, 2013). Discharge and surface mass budget for the northern Antarctic Peninsula (B25–26) are highly uncertain and only included for reference in Table 2. The complex basal topography, narrow glacial valleys and highly crevassed ice, make interpretation of the bed reflection in radar data difficult in this region. Estimating the surface mass budget is equally challenging with large interannual variability and steep spatial gradients in both precipitation and melt due to extreme surface topography over a large latitudinal range. For B25–26, we therefore rely on net mass budgets determined from glacier elevation changes within the 2003–2011 period that we update with estimated discharge changes for 2008–2015 (Scambos et al., 2014; Berthier et al., 2012; Shuman et al., 2017). A full discussion of the updated Antarctic Peninsula mass budget estimate is provided in Appendix B.

3 Results

3.1 Changes in surface velocity and ice discharge

By combining uncertainties of ice velocity and its relation to depth-averaged velocity, ice thickness, dynamic volume change and SMB for each flux-gate configuration, we estimate a total discharge uncertainty of 5.6 % for GL0, 4.5 % for FG1 and 2.1 % for FG2. The lower uncertainty for FG2 is due to the extensive use of RES data for ice thickness along the flux gate (Fig. 4). Hence, we use FG2 in combination with the Landsat velocity field to estimate total discharge. Obtaining continent-wide discharge for ~ 2008 using the SAR-based velocity field (Rignot et al., 2011a) at the FG2 flux gate is not possible due to data gaps inland of the grounding line. Instead, we estimate discharge change between the 2008 and Landsat mappings at FG1 and then subtract that from the Landsat estimate of discharge to obtain a total estimate for 2008. This approach reduces the impact of ice thickness errors at FG1 since they get scaled by velocity differences rather than by velocity magnitudes that are typically much larger. Thickness changes at FG1 and changes in the rate of dynamic volume change between FG1 and the grounding line occurring between 2008 and Landsat mappings were accounted for in the estimates of discharge change using the derived CryoSat-2 elevation change rates for 2011–2015 (see Sect. 2.6). Rates of volume change in 2008 and 2015 were extrapolated using the measured acceleration over the 2011–2015 period. Calculating flux in this way reduced the uncertainty in the total flux estimate generated from SAR velocities from $99\,\mathrm{Gt\,yr^{-1}}$ when calculating total discharge only at

Table 2. Surface area, cross sectional area for flux gate FG2, discharge corrected for dynamic volume change and surface mass balance between flux gate FG2 and the grounding line, basal melting, surface mass balance (SMB) and net mass balance for the 27 basins defined by Zwally et al. (2002). Cumulative numbers are provided for the East Antarctic Ice Sheet (EAIS: B2–17), the West Antarctic Ice Sheet (WAIS: B1, B18–23) and the Antarctic Peninsula (AP: B24–B27). Basal melt rates are from Van Liefferinge and Pattyn (2013) and calculated according to Pattyn (2010). SMB is calculated using the RACMO2.3 regional climate model at 5.5 km (van Wessem et al., 2016) resolution over the Antarctic Peninsula and 27 km elsewhere (van Wessem et al., 2014) and averaged over the 2008–2015 period. The net mass balance is calculated as the 2008–2015 SMB minus the average rate of discharge minus basal melt. Discharge for 2008 is derived from Rignot et al. (2011a) and for 2015 from the mean of the JPL 2015 error-weighted Landsat velocity mapping.

Basin	Area	Flux gate	Discharge ($Gt\,yr^{-1}$)			Basal melt	SMB ($Gt\,yr^{-1}$)	Net mass change	
	km^2	km^2	2008	2015	Δ	$Gt\,yr^{-1}$	2008–2015	$Gt\,yr^{-1}$	$kg\,m^{-2}\,yr^{-1}$
1	474 800	987 ± 53	110 ± 8	112 ± 7	2 ± 3	3 ± 0	121 ± 24	7 ± 25	16 ± 54
2	765 400	305 ± 33	48 ± 6	47 ± 4	−1 ± 4	3 ± 1	52 ± 10	2 ± 12	2 ± 16
3	1 556 600	213 ± 18	59 ± 4	60 ± 4	1 ± 2	5 ± 2	74 ± 15	9 ± 15	6 ± 10
4	241 200	351 ± 55	41 ± 8	43 ± 7	2 ± 3	1 ± 0	45 ± 9	2 ± 12	8 ± 50
5	185 300	196 ± 30	30 ± 5	31 ± 4	1 ± 2	1 ± 0	36 ± 7	5 ± 9	26 ± 47
6	607 700	501 ± 59	60 ± 7	60 ± 6	−1 ± 3	3 ± 0	81 ± 16	17 ± 17	28 ± 29
7	492 500	495 ± 62	68 ± 8	70 ± 8	2 ± 2	2 ± 0	93 ± 19	23 ± 20	46 ± 41
8	161 200	277 ± 32	17 ± 4	18 ± 3	1 ± 2	1 ± 0	36 ± 7	18 ± 8	111 ± 50
9	146 000	219 ± 18	17 ± 3	16 ± 2	−1 ± 2	1 ± 0	17 ± 3	0 ± 5	−1 ± 31
10	919 300	55 ± 5	34 ± 4	33 ± 3	−1 ± 2	3 ± 1	42 ± 8	6 ± 9	6 ± 10
11	255 200	187 ± 14	13 ± 3	12 ± 2	−1 ± 2	1 ± 1	16 ± 3	1 ± 4	6 ± 17
12	727 100	610 ± 74	102 ± 11	101 ± 10	0 ± 3	5 ± 1	128 ± 26	21 ± 28	29 ± 38
13	1 130 800	667 ± 50	226 ± 19	223 ± 18	−2 ± 5	7 ± 1	201 ± 40	−31 ± 45	−27 ± 39
14	718 500	714 ± 48	130 ± 10	130 ± 10	0 ± 3	5 ± 1	125 ± 25	−10 ± 27	−14 ± 38
15	123 800	190 ± 11	26 ± 6	26 ± 5	0 ± 2	1 ± 0	25 ± 5	−2 ± 8	−16 ± 62
16	262 000	159 ± 13	13 ± 2	14 ± 2	0 ± 2	1 ± 0	10 ± 2	−5 ± 3	−18 ± 12
17	1 825 800	646 ± 51	67 ± 8	67 ± 7	−1 ± 3	5 ± 2	78 ± 16	5 ± 18	3 ± 10
18	261 400	125 ± 16	9 ± 3	8 ± 2	−1 ± 2	2 ± 1	23 ± 5	13 ± 5	49 ± 21
19	367 700	258 ± 34	44 ± 6	45 ± 6	1 ± 2	3 ± 1	37 ± 7	−11 ± 10	−30 ± 26
20	180 100	490 ± 54	171 ± 15	183 ± 14	12 ± 4	2 ± 0	112 ± 22	−67 ± 27	−375 ± 149
21	207 500	179 ± 12	180 ± 12	189 ± 12	9 ± 4	2 ± 1	98 ± 20	−89 ± 23	−428 ± 111
22	210 200	112 ± 7	127 ± 8	134 ± 8	7 ± 2	2 ± 0	84 ± 17	−49 ± 19	−231 ± 89
23	74 600	249 ± 20	83 ± 8	83 ± 7	0 ± 3	1 ± 0	65 ± 13	−18 ± 15	−242 ± 204
24	100 600	211 ± 15	94 ± 7	95 ± 7	2 ± 3	1 ± 0	86 ± 17	−9 ± 19	−94 ± 186
25	34 700	78 ± 15	88 ± 13	91 ± 12	4 ± 5	0 ± 0	100 ± 20	−10 ± 21*	−297 ± 605*
26	42 000	116 ± 12	23 ± 4	25 ± 3	2 ± 2	1 ± 0	29 ± 6	−17 ± 7*	−406 ± 174*
27	52 000	89 ± 9	12 ± 3	12 ± 2	0 ± 2	0 ± 0	18 ± 4	6 ± 5	120 ± 88
EAIS	10 118 500	5786 ± 165	952 ± 31	952 ± 29	−1 ± 11	45 ± 4	1058 ± 66	61 ± 73	6 ± 7
WAIS	1 776 200	2400 ± 88	724 ± 24	754 ± 23	30 ± 8	16 ± 1	541 ± 45	−214 ± 51	−120 ± 29
AP	229 200	493 ± 26	217 ± 15	223 ± 14	7 ± 6	2 ± 0	234 ± 27	−31 ± 29	−133 ± 128
All	12 123 900	8679 ± 189	1894 ± 43	1929 ± 40	36 ± 15	63 ± 4	1834 ± 84	−183 ± 94	−15 ± 8

* Net mass balance for the northern Antarctic Peninsula (basins 25 and 26) is not determined using calculated discharge and SMB because of large and poorly constrained uncertainties in ice thickness and modeled SMB. Instead the net mass balance for basins 25 and 26 are determined by updating the mass balance estimate of Scambos et al. (2014) with changes in discharge determined here (see Appendix B).

the grounding line to $40\,Gt\,yr^{-1}$, a 60 % reduction in uncertainty, when applying this combined approach .

Comparing differences in discharge estimates between 6 Landsat velocity mappings (Fig. 7, 4 auto-RIFT v0.1, 2 LISA v1.0) shows good agreement despite differences in feature tracking methodologies, template chip size, horizontal resolution and time periods. The standard deviations between flux-change estimates are below the stated uncertainty in discharge listed in Table 2 for all 27 basins. Differences that do exist can be attributed to product errors. Auto-RIFT W15 has the lowest uncertainties, followed by auto-RIFT M15 then auto-RIFT W14 and M14 with the LISA 125 and 750 m products having the highest uncertainties (See Fig. A1). auto-RIFT uncertainties are lowest for the 2015 mapping simply due to a much larger number of available image pairs. The reason for higher uncertainties of the LISA products is not entirely known but is likely due to differences in geolocation offset correction and merging proce-

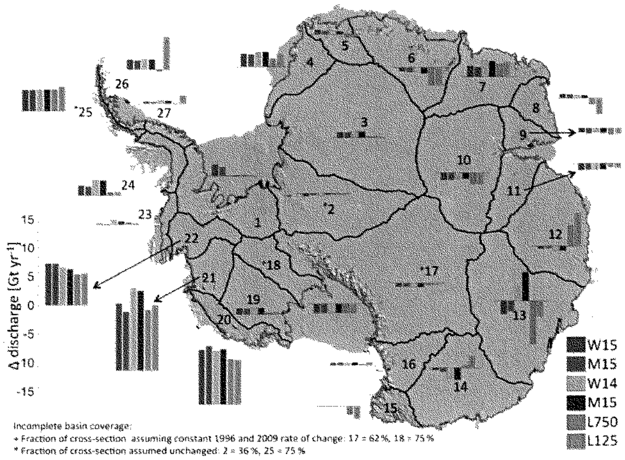

Figure 7. Change in flux across FG1 flux gate (shown with green line; see Methods) for the 27 basins defined by Zwally et al. (2002) calculated by differencing the pan-Antarctic SAR mapping of Rignot et al. (2011a, circa 2008) with six different Landsat 8 velocity mappings (M14/15 = JPL median of all 2014/15 image pairs; W14/15 = JPL weighted average of all 2014/15 image pairs; L750 = NSIDC 750 m average of all 2014–2015 image pairs; L125 = NSIDC 125 m average of all 2014–2015 image pairs). Basins 2, 17 and 18 are complimented with differences in 1997 and 2009 SAR velocities poleward of 82.5° S (Scheuchl et al., 2012). Much of the difference between velocity mappings can be attributed to product errors. W15 has the lowest uncertainties (used in this study), followed by M15, then W14 and M14, with the LISA products having the highest uncertainties (See Fig. A1).

dures. Some difference between mappings can also be expected due to real changes in ice flow between effective dates. This good agreement between products gives us confidence that our results are not sensitive to the Landsat processing methodology. From here forward we only present results generated using auto-RIFT W15 that provides the lowest uncertainties and longest period over which change in discharge is calculated.

3.1.1 Amundsen Sea

For the B21 and B22 catchments, containing Pine Island, Thwaites, Haynes, Pope, Smith and Kohler glaciers (Fig. 8), we find a 6 % increase in ice discharge or $17 \pm 4\,\mathrm{Gt\,yr^{-1}}$ (Table 2). This implies an average discharge increase of $2.4\,\mathrm{Gt\,yr^{-2}}$ for 2008–2015 that is considerably lower than the $6.5\,\mathrm{Gt\,yr^{-2}}$ previously estimated for 1994–2008 (Mouginot et al., 2014). This recent slowing in the rate of acceleration is in excellent agreement with the previously published temporally dense history of ice discharge that gave a rate of discharge increase for this region of $2.3\,\mathrm{Gt\,yr^{-2}}$ for overlapping but shorter period of 2010–2013 period (Mouginot et al., 2014). Pine Island and Thwaites glaciers both show clear signs of persistent dynamic drawdown, with velocities increasing by $> 100\,\mathrm{m\,yr^{-1}}$ up to 80–100 km inland from the grounding line (Fig. 9). Figure 9 shows a peak in Pine Island velocity change at 50 km and a secondary peak at 110 km upstream of the grounding line. We see no such peak when comparing between Landsat products, which makes us confident that the secondary peak is not an artifact of the Landsat processing. One possible non-geophysical explanation is that the radar mosaic includes data from a period significantly earlier than 2008 for area of the second peak. East Kohler and Smith glaciers also show extensive speedups throughout their length, with increases of $> 100\,\mathrm{m\,yr^{-1}}$ reaching more than 40 km inland likely driven by increased ocean melt rates and subsequent grounding-line retreat (Khazendar et al., 2016; Scheuchl et al., 2016). Patterns of velocity change for Pope and Kohler glaciers are more complex, with slowing of up to $100\,\mathrm{m\,yr^{-1}}$ near the grounding line and increased speed by $\sim 50\,\mathrm{m\,yr^{-1}}$ upstream reaching 40–80 km inland. This pattern of change is suggestive of an earlier period of dynamic drawdown that is slowly propagating inland contrasted by more recent deceleration near the grounding line. Glaciers feeding the Getz and Sulzberger ice shelves (B20; including Berry, Hull and Land glaciers) increased in speed by 10 to

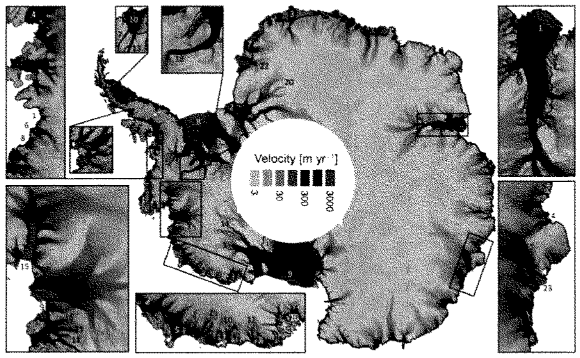

Figure 8. 2015 Antarctic ice sheet surface velocities shown in log scale determined from feature tracking of > 200 000 Landsat image pairs. Glacier and ice streams discussed in text labeled with black numbering: (1) Alison, (2) Berry, (3) Bindschadler, (4) Bond, (5) Evans, (6) Ferrigno, (7) Flask, (8) Fox, (9) Haynes, (10) Hull, (11) Kohler, (12) Land, (13) Leppard, (14) MacAyeal, (15) Pine Island, (16) Pope, (17) Prospect, (18) Rutford, (19) Seller, (20) Slessor, (21) Smith, (22) Stancomb-Wills, (23) Totten, and (24) Twaites. Ice shelves labeled with white numbering: (1) Amery, (2) Filchner, (3) Fimbul, (4) George VI, (5) Getz, (6) Moscow U., (7) Riiser-Larsen, (8) Ronne, (9) Ross, (10) Scar Inlet, and (10) Sulzberger.

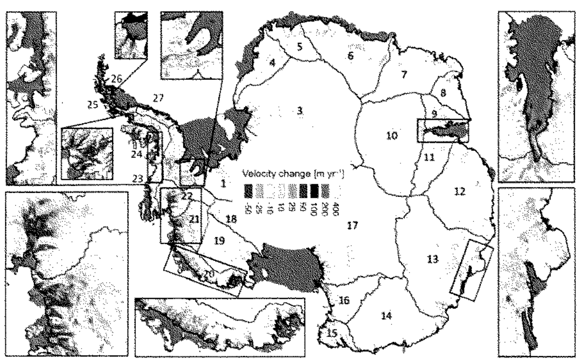

Figure 9. Change in surface velocities between date of pan-Antarctic SAR mapping (Rignot et al., 2011a, circa 2008) and new 2015 velocity mapping produced here from feature tracking of Landsat 8 imagery. Change in velocities shown for grounded ice only. Missing data shown in white and the 27 basin boundaries defined by Zwally et al. (2002) are shown in black.

$100\,m\,yr^{-1}$ at their grounding lines, increasing discharge by 6 % (Table 2). This result is in broad agreement with Chuter et al. (2017) that observed increases in ice velocity during the 2007–2013 period alongside 2010–2013 dynamic thinning rates of $0.7\,m\,yr^{-1}$ for the glaciers feeding the Abbot and Getz ice shelves.

3.1.2 Bellingshausen coast

Localized accelerations of 50–200 $m\,yr^{-1}$ are observed near grounding lines for several of the major glaciers along the Bellingshausen Coast (B23 and B24) including the Ferrigno, Fox and Alison ice streams and glaciers feeding into the southern George VI Ice Shelf. Despite some areas of flow acceleration, increases in discharge are highly localized. For many glaciers, the flux-gate cross section is decreasing from regional thinning, resulting in negligible changes in discharge. This result is unexpected, but with high confidence, as this region has experienced high rates of ice shelf thinning (Paolo et al., 2015) and grounding-line retreat (Christie et al., 2016), both of which were inferred to have resulted in accelerated dynamic thinning that contributed to a $56 \pm 8\,\mathrm{Gt\,yr^{-1}}$ increase in the rate of mass loss that began around 2009 and persisted until at least April 2014 (Wouters et al., 2015). From our analysis we conclude that any changes in discharge contributing to observed rates of thinning must have occurred prior to the SAR mapping of ice velocities. This result agrees with a recent investigation of longer-term (1995–2016) changes in ice discharge for this region (Hogg et al., 2017) that found that the region's glacier experienced an increase in ice discharge between 1995 and 2008 and almost no change in discharge between 2008 and 2016.

3.1.3 Northern Antarctic Peninsula

Along the west coast of the northern Antarctic Peninsula (B25) glaciers feeding into Marguerite Bay (Seller and Prospect) sped up by $400–800\,\mathrm{m\,yr^{-1}}$ at their grounding lines, the largest speedup of all Antarctic glaciers, with an increase of $> 100\,\mathrm{m\,yr^{-1}}$ reaching 10–15 km upstream. This speedup was recently attributed to increased ocean melt rates resulting from SOI/ENSO-driven ocean warming (Walker and Gardner, 2017). The majority of the west-coast glaciers to the north of Marguerite Bay are not sufficiently sampled in the earlier SAR mapping and are assumed to be unchanged between 2008 and 2015 (Fig. 2). Along the east coast of the northern Antarctic Peninsula (B26) most glaciers feeding into the former Larsen A and B ice shelves that collapsed in 1995 and 2002, respectively, either have not changed significantly or show signs of slowing near their grounding lines (Wuite et al., 2015), with the exception of Leppard and Flask glaciers. These two glaciers have sped up by $50–100\,\mathrm{m\,yr^{-1}}$ at their grounding lines, likely in response to reduced ice shelf buttressing and a resulting speedup of the abutting Scar Inlet Ice Shelf (Khazendar et al., 2015). Overall, this region shows a modest increase in ice discharge of $6 \pm 6\,\mathrm{Gt\,yr^{-1}}$, most of which comes from the glaciers flowing into Marguerite Bay. Small changes in rates of discharge between periods are in good agreement with constant rates of RACMO-derived surface mass budget and mass changes derived from GRACE data (Appendix B).

3.1.4 Ice streams feeding large ice shelves

Our analysis suggests a $5–20\,\mathrm{m\,yr^{-1}}$ slowdown of a broad region upstream of both Bindschadler and MacAyeal ice streams, which feed the Ross Ice Shelf. Ice streams feeding the Ronne-Filchner Ice Shelf show heterogeneous changes with slowing of $15–40\,\mathrm{m\,yr^{-1}}$ upstream of the Rutford and Evans ice stream grounding lines and $\sim 20\,\mathrm{m\,yr^{-1}}$ speedup of the Slessor Ice Stream. Slowing in the Rutford Ice Stream is consistent with the slowing observed between 1997 and 2009 (Scheuchl et al., 2012), but the apparent increase in velocity of the Slessor Ice Stream is of equal magnitude but of opposite sign to the changes observed between 1997 and 2009 (Scheuchl et al., 2012). Further to the east, the Stancomb-Wills Glacier increased in speed by $20–40\,\mathrm{m\,yr^{-1}}$, just upstream of the grounding line, with glaciers feeding the Riiser-Larsen, Fimbul and Amery ice shelves showing little change. Overall, changes in surface velocity along grounding lines of ice streams and glaciers feeding the major ice shelves of East and West Antarctica have not been large enough to significantly impact the net ice discharge for their respective basins (Table 2).

3.1.5 East Antarctic glaciers

Ice discharge has remained remarkably steady for the East Antarctic glaciers, particularly along the coasts of Dronning Maud Land and Enderby Land. These basins (B5–B8) showed very little change in ice discharge. The region to the west of Law Dome, including Underwood and Bond glaciers, shows subtle evidence of some increased flow speed and ice discharge, though the signal is near the limit of detection in part due to larger errors in the earlier radar mosaic for this region. However, the much larger Totten Glacier and the tributaries of the Moscow University Ice Shelf (B13) that drain a large fraction of the East Antarctic Ice Sheet show localized areas of ice speed variations but little change in discharge (Fig. 1). This result is consistent with recent findings of Li et al. (2016) showing that the Totten Glacier increased in velocity between 2001 and 2007, likely in response to elevated ocean temperature, but has been relatively unchanged since.

3.1.6 Antarctic discharge

In total we estimate that between the SAR and auto-RIFT W15 velocity mappings, the Antarctic ice sheet increased its solid ice discharge to the ocean from 1894 ± 43 to $1929 \pm 40\,\mathrm{Gt\,yr^{-1}}$. This represents a $36 \pm 15\,\mathrm{Gt\,yr^{-1}}$ increase in total discharge between 2008 and 2015; 78 % of the increases in discharge concentrated to glaciers flowing into the Amundsen Sea and another 10 % coming from glaciers flowing into Marguerite Bay. Breaking it down to the main ice-sheet regions, the discharge of the West Antarctic Ice Sheet (B1, B18–23) increased by $30 \pm 8\,\mathrm{Gt\,yr^{-1}}$ and the Antarctic Peninsula (B24–27) by $7 \pm 6\,\mathrm{Gt\,yr^{-1}}$, representing a 4 and 3 % increase in discharge, respectively. The discharge of the East Antarctic Ice Sheet (B2–17) was remarkably unchanged with a total discharge of 952 ± 31 and $952 \pm 29\,\mathrm{Gt\,yr^{-1}}$ in 2008 and 2015, respectively.

Our estimate of 2008 total Antarctic ice discharge ($1894 \pm 43\,\mathrm{yr^{-1}}$) is smaller than earlier estimates of 2048 ± 146 and $2049 \pm 86\,\mathrm{Gt\,yr^{-1}}$ by Rignot et al. (2013)

and Depoorter et al. (2013), respectively. Both earlier studies use the same SAR velocity mosaic as used here (Rignot et al., 2011a). Our estimate agrees with that of Rignot et al. (2013) within stated errors but not with that of Depoorter et al. (2013). Rignot et al. (2013) used Operation Ice Bridge and BEDMAP-2 ice thickness data at InSAR derived grounding lines to determine a total Antarctic discharge, with upscaling accounting for 352 Gt yr^{-1} of the total discharge. The most obvious reason for the difference in the central estimates is the definition of the flux gates. Rignot et al. (2013) mostly rely on BEDMAP-2 data while our study draws almost entirely from flight data. Another possible reason for the difference is the upscaling of results for unmeasured basins. For these basins the total discharge is assumed to be the modeled climatological average surface mass balance integrated over the upstream basin. Such estimates have not been adjusted for losses due to basal melt, and they are sensitive to errors in the modeled SMB and to the delineation of the contributing basin area over which SMB is integrated. Upscaling for unmeasured areas by Depoorter et al. (2013) accounted for 476 Gt yr^{-1} of their estimated discharge. The Depoorter et al. (2013) study uses a different definition of groundling but otherwise uses the same data as used in Rignot et al. (2013). Again, much of the difference between estimates can be attributed to the definition of ice thickness and upscaling to unmeasured basins. It should also be noted that Depoorter et al. (2013) and Rignot et al. (2013) both used output from an earlier version of RACMO that produced larger total SMB than the version of the model used in our study. Since SMB is used to upscale discharge, this likely contributes some to the larger discharge estimates. Similar conclusions were made for updated Greenland Ice Sheet discharge estimates that were lower than previous estimates (Enderlin et al., 2014).

3.2 Changes in net mass balance

For the West Antarctic Ice Sheet, the 2008–2015 net mass budgets were negative for all but two basins (B1 and B18) (Fig. 10), summing to a total imbalance of -214 ± 51 Gt yr^{-1} with largest rates of loss collocated with increased glacier velocities along the Amundsen Sea Embayment (B21 and B22) and Getz Ice Shelf (B20). The large mass loss for the Getz Ice Shelf region is in contrast to the near balance conditions recently reported by Chuter et al. (2017) for the 2006–2008 period but is in agreement with the 2010–2013 estimate of net mass change by Martín-Español et al. (2016). The East Antarctic Ice Sheet is found to have increased slightly in mass at a rate of 61 ± 73 Gt yr^{-1} with largest gains in Dronning Maud (B6) and Enderby Land (B7 and B8) that can be partially attributed to increase in precipitation rate (+28 Gt yr^{-1} relative to 1979–2007 mean) during the study period, which is consistent with earlier findings (Boening et al., 2012; King et al., 2012; Shepherd et al., 2012). For the whole of Antarctica, we estimate an average mass budget of -183 ± 94 Gt yr^{-1} for the 2008–2015 period. Other recent estimates of Antarctic mass change include those derived from CryoSat-2 altimetry of -159 ± 48 Gt yr^{-1} for the period 2010–2013 (McMillan et al., 2014) and -116 ± 76 Gt yr^{-1} for the period 2011–2014 (Helm et al., 2014, assuming density of ice) and a recent estimate from the joint inversion of gravity, altimetry and GPS data of -159 ± 22 Gt yr^{-1} for the period 2010–2013 (Martín-Español et al., 2016). All three studies show near balance to slightly positive mass changes for the East Antarctic Ice Sheet and large losses for the West Antarctic Ice Sheet and the Antarctic Peninsula, all of which agree well with the results presented here when considering uncertainties and differences in study periods.

4 Discussion

Areas of accelerated surface velocity (Fig. 9) and increased ice discharge are in good agreement with basin-scale assessment of changes in ice flow and ice discharge (Li et al., 2016; Mouginot et al., 2014) and with patterns of ice sheet thinning determined from laser and radar altimetry (Flament and Rémy, 2012; Helm et al., 2014; Pritchard et al., 2009). These show broad regions of surface lowering for glaciers feeding into the Amundsen Sea Embayment and Getz Ice Shelf and rapid drawdown of smaller glacier systems in the Antarctic Peninsula. Glaciers and ice streams feeding major ice shelves were remarkably steady with small heterogeneous changes in velocity. Apparent upstream slowing of Bindschadler and MacAyeal ice streams are at the limit of detectability and difficult to interpret. Recent assessments show varying changes in ice stream velocities for this region (Hulbe et al., 2016; Scheuchl et al., 2012), suggesting that measured trends may be influenced by rapid changes in the sub-ice-stream hydrology (Hulbe et al., 2016).

Strongly negative net mass budgets are apparent for the West Antarctic Ice Sheet and are largely due to mean rates of ice discharge greatly exceeding rates of snow accumulation. The basin-averaged results (Fig. 10) match remarkably well with patterns of pan-Antarctic multi-decadal (1994–2012) changes in ice shelf thickness (Paolo et al., 2015): high rates of mass loss from glaciers feeding into the Amundsen Sea are collocated with high rates of ice shelf thinning and near balance conditions for Wilkes Land glaciers and basins feeding the Filchner-Ronne, Ross and Amery ice shelves are collocated with ice shelves that have experienced little change in ice thickness over the past two decades. This result further supports the strong link between oceanic melting of ice shelves and ice sheet mass budget (Pritchard et al., 2012).

The link between basin mass budget and change in discharge is less obvious. This is primarily due to differences in representative periods as mass budgets represent the cumulative imbalance away from equilibrium state while changes in discharge are only representative of change in discharge

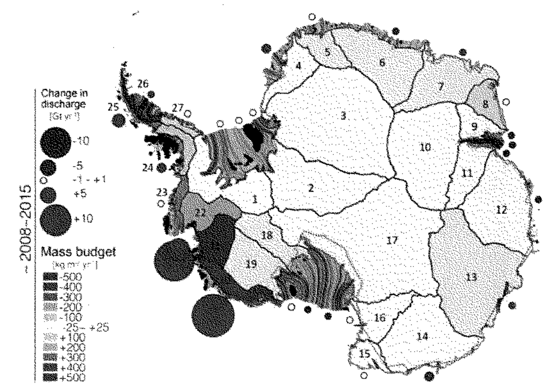

Figure 10. Mass budget and change in discharge for the 27 basins defined by Zwally et al. (2002). Mass budget is calculated as described in Table 2 using 2008–2015 average surface mass balance. Change in discharges (circles) calculated by differencing the pan-Antarctic SAR mapping of Rignot et al. (2011a; circa 2008) with weighted average of all 2015 image-pair displacements supplemented with 2009 SAR velocities to fill missing Landsat coverage poleward of 82.5° S (Scheuchl et al., 2012) with a correction for acquisition time differences to provide an estimate of total discharge for the interior basins (2, 17 and 18; see Table 2). Flux gates FG1 and FG2 are shown with solid green and dashed blue lines, respectively.

between two periods in time; e.g., a glacier can decelerate but still be discharging ice at a rate that exceeds the surface mass budget minus basal melt. Increased ice discharge from the Amundsen Sea Embayment and subsequent partial re-stabilization have been attributed to changes in ice shelf buttressing (Jacobs et al., 1996; Macgregor et al., 2012) that resulted from increased ice shelf basal melt rates (Jacobs et al., 2011; Jenkins et al., 1997) and more recently to a decrease in ocean melting resulting from changes in the temperature of intermediate depth waters (Dutrieux et al., 2014). Increased discharge from glaciers feeding into the Getz Ice Shelf is likely in response to rapid thinning of the ice shelf due to changes in ocean circulation and the depth of warmer modified Circumpolar Deep Water (Jacobs et al., 2013).

5 Conclusion

Applying novel feature tracking methods to hundreds of thousands of Landsat image pairs we are now able construct a detailed and comprehensive record of recent changes in Antarctic-wide ice flow. When combined with optimized flux-gate definitions and an earlier mapping of surface velocity (Rignot et al., 2011a), such measurements allow for accurate reconstructions of ice discharge and changes in ice discharge through time. Applying these new capabilities, we determine that the Antarctic ice sheet discharged $1894 \pm 43\,\mathrm{Gt\,yr^{-1}}$ of solid ice into the ocean in 2008, increasing to $1929 \pm 40\,\mathrm{Gt\,yr^{-1}}$ in 2015 with 78 % of the increase in discharge concentrated to glaciers flowing into the Amundsen Sea and another 10 % comes from glaciers flowing into Marguerite Bay. Glaciers and ice streams feeding major ice shelves were remarkably steady with small heterogeneous changes in velocity. Strongly negative net mass budgets are apparent for the West Antarctic Ice Sheet and are largely due to mean rates of ice discharge greatly exceeding rates of snow accumulation. The East Antarctic Ice Sheet experienced near-balance conditions with modest gains in Dronning Maud and Enderby Land driven by increased rates of precipitation.

Over the last decade, it is evident that larger-scale changes in discharge are relatively modest (< 7 % for all basins) compared to the fractional imbalance between discharge and surface mass budget (up to several tens of percent). This suggests that the recent pattern of mass loss in Antarctica, dominated by the Amundsen Sea sector, is likely a part of a longer-term phase of enhanced glacier flow initiated in the 1990s as indicated by satellite records (Konrad et al., 2017; Mouginot et al., 2014) or as early as the 1940s as proposed from sub-ice-shelf sediment records (Smith et al., 2017).

Glaciology is rapidly transitioning from an observationally constrained environment to one with ample high-quality, high-volume satellite data sets suitable for mapping ice flow on continental scales (e.g., Landsat 8, Sentinel 2a/b, Sentinel 1a/b). This study provides a foundation for continued assessment of ice sheet flow and discharge that will allow researches to observe both large and subtle changes ice sheet flow that may indicate early signs of ice sheet instability with low latency. Such a capability would help to diagnose unstable flow behavior and, in conjunction with high accuracy measurements of ice sheet elevation and mass change, would lead to improved assessment ice sheet surface mass balance and ice shelf melt rates. Low-latency monitoring of ice flow and discharge would also allow field programs, flight planning and satellite tasking to coordinate the collection of complimentary observations in areas of changing ice behavior. These advances will ultimately lead to a deeper understanding of the causal mechanisms resulting in observed and future ice sheet instabilities. Any substantial improvement in our assessment of ice sheet discharge will require more detailed knowledge of ice thickness just upstream of the grounding line, particularly for areas of complex flow such as the Antarctic Peninsula and Victoria Land. Errors in discharge estimates can be greatly reduced if thickness profiles are acquired perpendicular to ice flow. Improved estimates of net mass change calculated using the mass budget approach will come from continued refinement of regional climate models and better estimates of basal melt.

Data availability. All velocity mosaics, grounding lines, flux gates and ancillary data are available from the National Snow and Ice Data Center (Gardner et al., 2018a, b; Fahnestock et al., 2016).

Appendix A: Uncertainty quantification

A1 Ice discharge

The uncertainty in flux estimates were calculated for each of the 27 basins as

$$\sigma F = \sqrt{\sigma F_H^2 + \sigma F_{\mathrm{d}H}^2 + \sigma F_V^2 + \sigma F_{\mathrm{SMB}}^2 + \sigma F_{\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t}^2 + \sigma F_{\mathrm{bm}}^2} + \sigma F_{\overline{V}}, \tag{A1}$$

where σF_H is due to uncertainties in ice-equivalent thickness, $\sigma F_{\mathrm{d}H}$ is due to uncertainties in the change of ice-equivalent thickness between the measurement times of ice thickness and surface velocity, and σF_V is due to uncertainties in measured velocity. $\sigma F_{\overline{V}}$ is due to the assumption that the depth-averaged velocity ($\overline{V}$) is equal to the surface velocity and is added as a bias (outside of the quadrature sum) to both sides of the error envelope for simplicity. $\sigma F_{\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t}$, σF_{SMB} and σF_{bm} are uncertainties introduced by dynamic volume change, surface mass balance and basal melt corrections applied between the flux gate and the true grounding line. $\sigma F_{\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t}$ was taken to be 0.1 m yr^{-1} for surfaces moving faster than 200 m yr^{-1}. σF_{SMB} was taken to be 20 % of the SMB. Uncertainties in flux resulting from uncertainties in ice thickness, changes in ice thickness and surface velocity were propagated assuming a conservative correlation length along the flux gate as follows:

$$\sigma F_H = \sqrt{\sum_1^{n_H} \left(\sum_{i=1}^{m_H} \sigma H_i W_i V_i \right)^2}, \tag{A2}$$

$$\sigma F_{\mathrm{d}H} = \sqrt{\sum_1^{n_{\mathrm{d}H}} \left(\sum_{i=1}^{m_{\mathrm{d}H}} \sigma \frac{\mathrm{d}H}{\mathrm{d}t}_i \mathrm{d}t_i W_i V_i \right)^2}, \tag{A3}$$

$$\sigma F_V = \sqrt{\sum_1^{n_V} \left(\sum_{i=1}^{m_V} \sigma V_i W_i H_i \right)^2} + \sum_{i=1}^{\mathrm{nn}} \sigma V_{0i} W_i H_i, \tag{A4}$$

where m is the number of point estimates of flux (x) for each correlation length distance along the flux gate and n is the number of discrete uncorrelated lengths for each basin for measurements of ice thickness (H), changes in ice thickness ($\mathrm{d}H$) and the surface velocity normal to the flux gate (V). Uncertainties in ice thickness (σH_i) are taken as the RSS of the thickness estimate and the FAC. Uncertainties in changes in ice thickness ($\sigma \frac{\mathrm{d}H}{\mathrm{d}t}$) are determined as the RSS of uncertainty due to changes in FAC and surface elevation. $\mathrm{d}t$ is the difference in time between the measurement of ice thickness and the measurement of surface velocity. σF_V is modeled using a velocity uncertainty component σV_0 that is fully correlated at lengths smaller than an estimated correlation length and uncorrelated at larger lengths (σV). Comparing Landsat and SAR velocities measured at flux-gate nodes for basins with minimal change in ice discharge (B1–19 and B27); i.e., where velocity differences are assumed to be indicative measurement uncertainty, we were able to model the observed

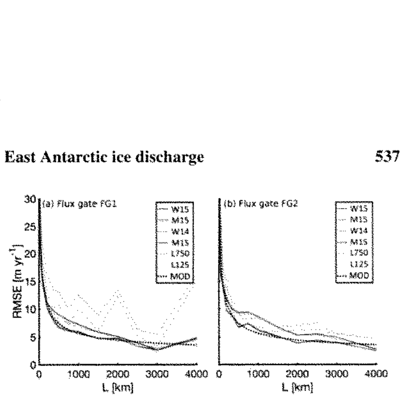

Figure A1. RMSE of the Landsat component of velocity that is normal to the flux-gate cross section at FG1 **(a)** and FG2 **(b)** flux nodes relative to ~ 2008 SAR velocities (Rignot et al., 2011a) as a function of averaging distance (L). MOD is the modeled uncertainty assuming a fully correlated uncertainty of 1 m yr^{-1} plus a 3 m yr^{-1} uncertainty that is uncorrelated at distances greater than 1000 km.

RMSE between Landsat and SAR observations (Fig. A1) setting $\sigma V_0 = 3$ m yr^{-1} and $\sigma V = 1$ m yr^{-1} with a correlation length of 1000 km for both the SAR and Landsat mappings. Uncertainties in velocities can be as high as 20–30 m yr^{-1} locally but are largely uncorrelated on basin scales. There are insufficient data to determine rigorous estimates of the correlation lengths for ice thickness, change in ice thickness and surface velocity, all of which are likely spatially variable. Instead we took a conservative approach and assigned a correlation length of 1000 km to all three measurements.

When calculating ice flux we assumed that the surface velocity was equal to the depth-averaged velocity. This approach neglects vertical gradients in ice velocity that result from the stress-dependent plastic deformation (creep) of ice. Since surface velocities are always larger than the depth-averaged velocity this introduced a positive bias into our estimates of ice flux. Neglecting sliding and assuming a depth constant creep parameter (A) the depth-averaged velocity is 80 % of the surface velocity (Cuffey and Paterson, 2010). Assuming parallel flow and a linear increase in shear stress with depth, the surface velocity due to creep (V_s) can be calculated as follows:

$$V_\mathrm{s} = \frac{2A}{1+n} t_\mathrm{b}^n H, \tag{A5}$$

where n is the creep exponent, H is the ice thickness and t_b is the driving stress at the bed. n is typically assumed to be 3 and so is done here. t_b is calculated using the surface slope and ice depth (Cuffey and Paterson, 2010). The creep parameter A (Fig. A2a) is taken from Ice Sheet System Model (ISSM) output generated as part of the Sea-level Response to Ice Sheet Evolution (SeaRISE) experiments (Bindschadler et al., 2013). We calculated surface slope from a CryoSat-2 DEM that was smoothed on a scale of several times the ice thickness (20 km). Ice thickness was taken from Bedmap-2 (Fretwell et al., 2013). V_s varied between 0 m yr^{-1} at the ice divides and 10 m yr^{-1} in steeply sloped outlet glaciers near

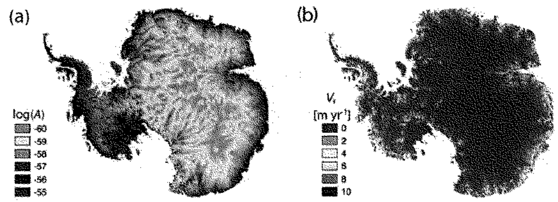

Figure A2. Creep parameter (A: s^{-1} Pa^{-3}) shown in log scale **(a)**. Estimated surface velocity due to ice creep (V_s).

the coast (Fig. A2b). We considered 20 % of V_s to be the upper bound of the bias introduced into our flux estimates due to vertical gradients in the velocity field ($\sigma F_{\overline{V}}$), calculated as

$$\sigma F_{\overline{V}} = 0.2 \sum_{x=1}^{\mathrm{nn}} V_{si} W_i H_i, \tag{A6}$$

where nn is the number nodes along the basin flux gate. This is an upper bound scenario, as A increases rapidly with temperature, and ice sheet temperature is typically at a maximum near the bed. This results in a higher concentration of shear deformation near the base of the ice sheet than inferred from a depth-constant A.

Uncertainties in flux estimates were assumed to be uncorrelated between basins. A detailed accounting of each flux term and their associated error is provided in Tables A1 through A3. Table A1 provides detailed breakdown for the total discharge calculated using FG2 as the flux gate. This approach produces the discharge estimate with the lowest error and is the approach used in the main paper. For comparison, Tables A2 and A3 provide detailed breakdowns for the total discharge calculated using FG1 and GL0, respectively.

A2 Change in ice discharge

Uncertainty in flux-change estimates ($\sigma \mathrm{d}F$) are calculated as

$$\sigma \mathrm{d}F = \sqrt{\sigma \mathrm{d}F_H^2 + \sigma \mathrm{d}F_{\mathrm{d}H}^2 + \sigma \mathrm{d}F_V^2 + \sigma \mathrm{d}F_{\mathrm{no\_data}}^2}, \tag{A7}$$

where $\sigma \mathrm{d}F_H$ is the thickness-related uncertainty and is calculated as

$$\sigma \mathrm{d}F_H = \sigma F_{H0} \frac{\mathrm{d}F}{F}, \tag{A8}$$

where $\mathrm{d}F$ is the change in flux and F is the total flux. $\sigma \mathrm{d}F_{\mathrm{d}H}$ is calculated in the same way as $\sigma F_{\mathrm{d}H}$ but setting $\mathrm{d}t$ to the time separation between repeat measurements of velocity. $\sigma \mathrm{d}F_v$ is the flux-change uncertainty from the measured velocity and is determined as

$$\sigma \mathrm{d}F_v = \sqrt{\sigma F_{v1}^2 + \sigma \mathrm{d}F_{v2}^2}, \tag{A9}$$

where σF_v is the uncertainty in flux introduced from uncertainties in surface velocity for two measurement epochs (1 and 2). $\sigma \mathrm{d}F_{\mathrm{no\_data}}$ is the flux-change uncertainty introduced by the assumption of zero change in flux for areas lacking reliable repeat measurements ($\sigma F_{\mathrm{no\_data}}$) and for areas between the flux gate and the grounding line (σF_{SMB}) and is calculated as

$$\sigma \mathrm{d}F_{\mathrm{no\_data}} = 0.1 \left(\sigma F_{\mathrm{SMB}} + \sigma F_{\mathrm{no\_data}}\right). \tag{A10}$$

Uncertainties in flux-change estimates were assumed to be uncorrelated between basins. A detailed accounting of each change in flux term and their associated error is provided in Table A4.

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Table A1. Detailed breakdown of total discharge estimate (D) presented in Table 2 using JPL auto-RIFT 2015 weighted average velocity (W15), FG2 flux gate and GL0 grounding line. Surface areas are for the total basin area upstream of the grounding line, flux gate and the area between the flux gate and the grounding line. F is the total flux across the flux gate. SMB, BM and $\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t$ are the surface mass balance, basal melt and dynamic volume change integrated over the area between the flux gate and the grounding line. All error terms and their propagation are describe in Sect. A1.

ID basin	Surface area (km^2)			Length (km)	Flux through FG2 (Gt yr^{-1})						Additional flux between FG2 and GL0 [Gt yr^{-1}]						Total discharge (Gt yr^{-1})	
	GL0	FG2	GL0 – FG2	FG2	F	σF_H	$\sigma F_{\mathrm{d}H}$	σF_V	$\sigma F_{V\_\mathrm{bar}}$	σF	SMB	σF_{SMB}	BM	σF_{BM}	$\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t$	$\sigma F_{\mathrm{d}V_{\mathrm{dyn}}/\mathrm{d}t}$	D	σD
1	474 821	463 896	10 926	1170	108.8	5.6	0.3	3.3	0.2	6.8	2.7	0.5	0.0	0.0	0.1	0.2	111.7	6.8
2	765 381	757 558	7824	359	46.0	3.2	0.0	1.8	0.1	3.7	0.9	0.2	0.0	0.0	0.2	0.1	47.1	3.7
3	1 556 551	1 545 527	11 024	253	58.1	3.4	0.1	1.6	0.0	3.8	1.6	0.3	0.0	0.0	0.0	0.1	59.8	3.8
4	241 158	226 961	14 197	680	39.5	7.0	0.4	2.0	0.1	7.4	3.8	0.8	−0.1	0.0	−0.1	0.2	43.3	7.4
5	185 337	182 253	3084	415	29.3	4.0	0.4	1.5	0.1	4.4	1.6	0.3	0.0	0.0	−0.1	0.0	30.8	4.4
6	607 737	583 513	24 224	740	53.8	5.3	0.2	2.4	0.2	6.0	6.0	1.2	−0.2	0.0	−0.2	0.2	59.7	6.1
7	492 518	451 677	40 841	799	49.1	5.9	0.3	2.4	0.2	6.6	20.6	4.1	−0.4	0.0	−0.3	0.6	69.9	7.9
8	161 243	144 458	16 785	485	11.9	1.9	0.2	1.8	0.1	2.7	6.2	1.2	−0.2	0.0	−0.5	0.1	17.7	3.0
9	146 003	140 392	5612	386	15.0	1.1	0.2	1.6	0.1	2.0	1.3	0.3	0.0	0.0	0.0	0.1	16.4	2.1
10	919 320	918 041	1278	56	33.0	2.9	0.2	1.2	0.1	3.2	0.0	0.0	0.0	0.0	0.0	0.1	33.1	3.2
11	255 178	249 424	5753	275	11.9	0.7	0.1	1.5	0.7	2.4	0.4	0.1	−0.1	0.0	0.0	0.1	12.3	2.4
12	727 088	698 205	28 883	882	89.0	8.8	0.6	2.7	1.0	10.2	11.0	2.2	−0.6	0.0	0.7	0.8	101.2	10.5
13	1 130 843	1 095 837	35 006	804	192.7	15.9	0.9	2.8	1.4	17.5	27.5	5.5	−0.7	0.0	2.5	1.0	223.3	18.5
14	718 511	667 028	51 483	734	102.2	6.7	0.5	3.0	0.5	7.9	26.9	5.4	−0.8	0.0	0.1	0.8	130.0	9.7
15	123 780	14 735	109 044	187	1.3	0.1	0.0	1.5	0.1	1.7	24.5	4.9	−0.5	0.1	0.2	0.4	26.4	5.3
16	262 005	236 067	25 937	339	10.7	0.7	0.1	1.4	0.0	1.6	2.9	0.6	−0.2	0.0	0.0	0.1	13.7	1.7
17	1 825 799	1 667 954	157 845	775	46.0	3.8	0.2	2.8	0.4	5.2	22.9	4.6	−0.4	0.0	−2.3	1.8	67.0	7.3
18	261 357	234 457	26 900	185	7.4	1.1	0.0	1.3	0.0	1.7	2.0	0.4	0.0	0.0	−1.9	1.2	7.5	2.2
19	367 678	347 019	20 659	353	42.9	5.6	0.1	1.7	0.0	5.8	2.4	0.5	−0.1	0.0	0.1	0.8	45.5	5.9
20	180 072	139 929	40 143	714	140.6	11.4	0.9	2.3	0.5	12.2	33.9	6.8	−0.5	0.0	8.2	2.5	183.2	14.3
21	207 491	203 265	4227	276	180.8	11.1	0.7	1.5	0.2	11.4	4.7	0.9	−0.1	0.0	3.7	1.1	189.3	11.5
22	210 237	206 351	3886	177	130.9	7.8	0.3	1.3	0.0	7.9	2.8	0.6	0.0	0.0	0.8	0.2	134.5	7.9
23	74 562	53 294	21 269	396	60.6	5.1	0.6	1.7	0.3	5.7	20.2	4.0	−0.3	0.0	1.5	0.5	82.5	7.0
24	100 567	93 479	7088	429	86.3	5.9	0.5	1.6	0.2	6.3	7.5	1.5	−0.1	0.0	1.3	0.4	95.2	6.5
25	34 657	18 312	16 345	475	34.4	3.5	0.8	1.2	0.2	3.9	54.9	11.0	−0.1	0.0	2.0	0.6	91.4	11.8
26	42 025	30 162	11 863	469	17.3	1.7	0.4	1.3	0.5	2.7	7.2	1.4	0.0	0.0	0.2	0.1	24.7	3.1
27	51 962	40 319	11 643	297	6.9	0.6	0.1	1.2	0.0	1.4	5.0	1.0	0.0	0.0	0.0	0.0	11.9	1.7
Total	12 123 881	11 410 110	713 770	13 108	1606.3	31.8	2.2	10.2	2.2	35.2	301.5	17.9	−5.3	0.1	16.1	4.1	1929.2	39.9

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Table A2. Same as Table A1 but using the FG1 for the flux gate.

ID basin	Surface area (km^2)			Length (km)	Flux through FG1 (Gt yr^{-1})						Additional flux between FG1 and GL0 (Gt yr^{-1})						Total discharge (Gt yr^{-1})	
	GL0	FG1	GL0 – FG1	FG1	F	σF_H	σF_{dH}	σF_V	σF_{V_bar}	σF	SMB	σF_{SMB}	BM	σF_{BM}	dV_{dyn}/dt	$\sigma F_{dV_{dyn}/dt}$	D	σD
1	474 821	466 855	7967	1287	109.8	5.3	0.3	3.2	0.2	6.5	1.8	0.4	0.0	0.0	0.1	0.2	111.7	6.5
2	765 381	761 534	3847	370	46.9	2.9	0.1	1.9	0.0	3.6	0.5	0.1	0.0	0.0	0.2	0.1	47.5	3.6
3	1 556 551	1 553 115	3437	299	59.6	3.8	0.1	1.6	0.0	4.2	0.3	0.1	0.0	0.0	0.0	0.1	60.0	4.2
4	241 158	239 208	1950	843	44.5	10.7	0.5	1.9	0.0	10.9	0.6	0.1	0.0	0.0	0.0	0.0	45.1	10.9
5	185 337	184 737	600	489	30.4	4.6	0.4	1.6	0.1	5.0	0.2	0.0	0.0	0.0	0.0	0.0	30.6	5.0
6	607 737	604 178	3559	1080	59.0	9.1	0.2	2.3	0.1	9.4	0.8	0.2	0.0	0.0	−0.2	0.1	59.7	9.4
7	492 518	492 159	359	1253	45.1	23.0	1.4	1.6	0.0	23.1	0.2	0.0	0.0	0.0	0.0	0.0	45.3	23.1
8	161 243	160 984	259	554	14.8	7.3	0.4	1.4	0.0	7.5	0.2	0.0	0.0	0.0	0.0	0.0	14.9	7.5
9	146 003	145 979	24	466	14.5	2.0	0.1	1.7	0.0	2.7	0.0	0.0	0.0	0.0	0.0	0.0	14.5	2.7
10	919 320	919 149	171	36	37.3	3.6	0.1	1.2	0.2	4.0	0.0	0.0	0.0	0.0	0.0	0.0	37.3	4.0
11	255 178	255 033	145	333	9.0	1.3	0.1	1.6	0.8	2.8	0.0	0.0	0.0	0.0	0.0	0.0	9.0	2.8
12	727 088	726 521	567	1072	124.6	38.6	1.8	2.0	0.1	38.8	0.3	0.1	0.0	0.0	0.0	0.0	124.9	38.8
13	1 130 843	1 125 684	5159	1005	202.3	35.7	2.0	2.6	1.1	36.9	4.1	0.8	−0.1	0.0	1.3	0.4	207.8	36.9
14	718 511	716 677	1834	1129	134.0	24.6	1.6	2.2	0.1	24.8	1.2	0.2	0.0	0.0	0.1	0.1	135.3	24.8
15	123 780	123 620	160	1102	19.7	14.0	0.4	1.7	0.7	14.8	0.0	0.0	0.0	0.0	0.0	0.0	19.7	14.8
16	262 005	261 418	587	554	7.2	1.7	0.2	1.2	0.0	2.1	0.0	0.0	0.0	0.0	0.0	0.0	7.2	2.1
17	1 825 799	1 823 861	1938	1235	53.8	10.9	0.3	2.1	0.1	11.2	0.3	0.1	0.0	0.0	−0.1	0.1	53.9	11.2
18	261 357	259 869	1488	444	10.6	2.0	0.1	1.6	0.0	2.6	0.1	0.0	0.0	0.0	−0.1	0.0	10.6	2.6
19	367 678	366 585	1094	419	44.9	6.2	0.1	1.7	0.0	6.4	0.1	0.0	0.0	0.0	0.0	0.1	45.0	6.4
20	180 072	173 181	6891	1382	146.9	23.4	1.1	2.1	0.4	23.9	7.4	1.5	−0.2	0.0	6.1	1.8	160.6	24.0
21	207 491	205 221	2271	326	181.9	11.9	0.8	1.5	0.2	12.2	2.3	0.5	−0.1	0.0	3.7	1.1	188.0	12.3
22	210 237	208 363	1874	219	132.1	8.4	0.4	1.3	0.0	8.6	1.3	0.3	0.0	0.0	0.8	0.2	134.2	8.6
23	74 562	72 800	1763	881	78.2	17.3	1.1	1.9	0.0	17.4	2.7	0.5	0.0	0.0	0.7	0.2	81.6	17.5
24	100 567	97 297	3271	511	88.1	8.9	0.7	1.6	0.2	9.3	2.9	0.6	0.0	0.0	1.0	0.3	92.0	9.3
25	34 657	33 834	823	1360	62.9	25.6	1.9	1.3	0.0	25.8	1.7	0.3	0.0	0.0	0.8	0.2	65.4	25.8
26	42 025	41 888	138	1300	26.1	7.7	0.6	1.5	0.5	8.4	0.0	0.0	0.0	0.0	0.0	0.0	26.2	8.4
27	51 962	51 562	400	703	8.9	2.4	0.1	1.5	0.0	2.8	0.2	0.0	0.0	0.0	0.0	0.0	9.1	2.8
Total	12 123 881	12 071 309	52 572	20 653	1792.9	80.3	4.6	9.5	1.7	82.0	29.3	2.0	−0.6	0.0	14.4	2.3	1837.3	82.1

Table A3. Same as Table A1 but using the GL0 for the flux gate.

ID basin	Surface area (km^2)			Length (km)	Flux through FG1 ($Gt\,yr^{-1}$)						Additional flux between FG1 and GL0 [$Gt\,yr^{-1}$]						Total discharge ($Gt\,yr^{-1}$)	
	GL0	GL0	GL0 – GL0	GL0	F	σF_H	σF_{dH}	σF_V	σF_{V_bar}	σF	SMB	σF_{SMB}	BM	σF_{BM}	dV_{dyn}/dt	$\sigma F_{dV_{dyn}/dt}$	D	σD
1	474 821	474 821	0	1651	112.1	8.2	0.3	3.9	0.4	9.5	0.0	0.0	0.0	0.0	0.0	0.0	112.1	9.5
2	765 381	765 381	0	457	39.4	4.0	0.1	2.3	0.0	4.6	0.0	0.0	0.0	0.0	0.0	0.0	39.4	4.6
3	1 556 551	1 556 551	0	325	50.9	7.4	0.2	1.7	0.0	7.6	0.0	0.0	0.0	0.0	0.0	0.0	50.9	7.6
4	241 158	241 158	0	920	47.3	14.2	0.6	2.0	0.0	14.4	0.0	0.0	0.0	0.0	0.0	0.0	47.3	14.4
5	185 337	185 337	0	530	29.2	5.0	0.4	1.7	0.1	5.3	0.0	0.0	0.0	0.0	0.0	0.0	29.2	5.3
6	607 737	607 737	0	1144	58.5	13.2	0.3	2.2	0.0	13.4	0.0	0.0	0.0	0.0	0.0	0.0	58.5	13.4
7	492 518	492 518	0	1265	44.5	22.5	1.4	1.6	0.0	22.6	0.0	0.0	0.0	0.0	0.0	0.0	44.5	22.6
8	161 243	161 243	0	574	13.7	6.9	0.4	1.4	0.0	7.0	0.0	0.0	0.0	0.0	0.0	0.0	13.7	7.0
9	146 003	146 003	0	554	14.1	2.0	0.2	1.9	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	14.1	2.8
10	919 320	919 320	0	35	33.4	3.2	0.1	1.2	0.2	3.5	0.0	0.0	0.0	0.0	0.0	0.0	33.4	3.5
11	255 178	255 178	0	343	8.8	1.3	0.1	1.6	0.8	2.9	0.0	0.0	0.0	0.0	0.0	0.0	8.8	2.9
12	727 088	727 088	0	1144	125.7	40.2	1.9	2.1	0.1	40.4	0.0	0.0	0.0	0.0	0.0	0.0	125.7	40.4
13	1 130 843	1 130 843	0	1248	202.6	37.7	1.9	2.8	0.4	38.2	0.0	0.0	0.0	0.0	0.0	0.0	202.6	38.2
14	718 511	718 511	0	1162	129.7	32.4	1.8	2.1	0.0	32.6	0.0	0.0	0.0	0.0	0.0	0.0	129.7	32.6
15	123 780	123 780	0	1121	20.3	14.3	0.4	1.7	0.8	15.2	0.0	0.0	0.0	0.0	0.0	0.0	20.3	15.2
16	262 005	262 005	0	597	7.5	2.2	0.2	1.3	0.0	2.6	0.0	0.0	0.0	0.0	0.0	0.0	7.5	2.6
17	1 825 799	1 825 799	0	1288	53.3	9.9	0.3	2.2	0.1	10.3	0.0	0.0	0.0	0.0	0.0	0.0	53.3	10.3
18	261 357	261 357	0	510	10.4	2.2	0.1	1.7	0.0	2.8	0.0	0.0	0.0	0.0	0.0	0.0	10.4	2.8
19	367 678	367 678	0	540	44.6	6.9	0.2	1.9	0.0	7.1	0.0	0.0	0.0	0.0	0.0	0.0	44.6	7.1
20	180 072	180 072	0	1581	139.2	34.6	1.3	2.2	0.1	34.7	0.0	0.0	0.0	0.0	0.0	0.0	139.2	34.7
21	207 491	207 491	0	370	181.7	16.1	1.5	1.6	0.2	16.4	0.0	0.0	0.0	0.0	0.0	0.0	181.7	16.4
22	210 237	210 237	0	266	128.9	10.6	0.5	1.3	0.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0	128.9	10.7
23	74 562	74 562	0	936	80.7	24.6	1.4	1.9	0.0	24.7	0.0	0.0	0.0	0.0	0.0	0.0	80.7	24.7
24	100 567	100 567	0	557	78.7	23.0	1.4	1.5	0.0	23.1	0.0	0.0	0.0	0.0	0.0	0.0	78.7	23.1
25	34 657	34 657	0	1323	62.4	35.4	2.4	1.3	0.0	35.5	0.0	0.0	0.0	0.0	0.0	0.0	62.4	35.5
26	42 025	42 025	0	1326	27.5	8.9	0.7	1.5	0.2	9.2	0.0	0.0	0.0	0.0	0.0	0.0	27.5	9.2
27	51 962	51 962	0	784	10.6	4.7	0.3	1.5	0.0	4.9	0.0	0.0	0.0	0.0	0.0	0.0	10.6	4.9
Total	12 123 881	12 123 881	0	22 550	1755.6	98.0	5.3	10.1	1.3	99.2	0.0	0.0	0.0	0.0	0.0	0.0	1755.6	99.2

Table A4. Detailed breakdown of the change in discharge (ΔD) estimate presented in Table 2 using JPL auto-RIFT 2015 weighted average velocity (W15), ~2008 velocities from Rignot et al. (2011a), the FG1 flux gate and GL0 grounding line. $\mathrm{d}F$ is change in flux across the grounding line and $\mathrm{dd}V_{\mathrm{dyn}}/\mathrm{d}t$ is the change in dynamic volume change for the area between FG1 and GL0. All error terms and their propagation are describe in Sect. A2.

ID basin	Surface area (km^2)			Length (km)	Δ flux through FG1 (Gt yr^{-1})					Additional Δ flux between FG1 and GL [Gt yr^{-1}]	Total Δ discharge (Gt yr^{-1})	
	GL	FG1	GL – FG1	FG1	$\mathrm{d}F$	$\sigma \mathrm{d}F_H$	$\sigma \mathrm{d}F_{\mathrm{d}H}$	$\sigma \mathrm{d}F_V$	$\sigma \mathrm{d}F_{\mathrm{no\_data}}$	$\mathrm{dd}V_{\mathrm{dyn}}/\mathrm{d}t$	$\mathrm{d}D$	$\sigma \mathrm{d}D$
1	474 821	466 855	7967	1287	2.0	0.1	0.6	3.0	1.1	−0.4	1.6	3.2
2	765 381	761 534	3847	370	−0.5	0.0	0.1	2.0	3.8	−0.3	−0.8	4.3
3	1 556 551	1 553 115	3437	299	0.8	0.0	0.4	2.1	0.1	−0.1	0.7	2.2
4	241 158	239 208	1950	843	2.2	0.4	1.0	2.4	0.4	0.0	2.2	2.7
5	185 337	184 737	600	489	0.7	0.1	0.8	2.0	0.3	0.1	0.7	2.2
6	607 737	604 178	3559	1080	−0.6	0.1	0.7	2.5	0.6	0.2	−0.3	2.7
7	492 518	492 159	359	1253	1.9	0.2	0.7	2.1	0.3	0.0	1.9	2.2
8	161 243	160 984	259	554	0.7	0.1	0.4	1.9	0.0	0.0	0.7	2.0
9	146 003	145 979	24	466	−0.7	0.1	0.2	2.2	0.0	−0.1	−0.8	2.2
10	919 320	919 149	171	36	−1.2	0.1	0.3	1.6	0.0	0.0	−1.2	1.7
11	255 178	255 033	145	333	−1.2	0.1	0.1	2.0	0.0	0.0	−1.1	2.0
12	727 088	726 521	567	1072	−0.3	0.0	1.3	2.8	0.4	0.0	−0.3	3.1
13	1 130 843	1 125 684	5159	1005	−2.3	0.2	2.3	3.3	2.8	0.0	−2.3	4.9
14	718 511	716 677	1834	1129	−0.4	0.0	1.5	2.8	0.5	0.4	0.0	3.2
15	123 780	123 620	160	1102	0.0	0.0	0.0	2.3	0.0	0.0	0.0	2.3
16	262 005	261 418	587	554	0.3	0.0	0.3	1.7	0.0	0.0	0.4	1.7
17	1 825 799	1 823 861	1938	1235	−0.5	0.0	0.4	2.1	2.5	0.2	−0.3	3.3
18	261 357	259 869	1488	444	−1.5	0.0	0.0	1.4	1.2	0.1	−1.4	1.9
19	367 678	366 585	1094	419	1.0	0.1	0.3	2.0	0.1	0.2	1.2	2.0
20	180 072	173 181	6891	1382	11.6	0.9	2.6	2.8	1.1	0.7	12.2	4.1
21	207 491	205 221	2271	326	9.4	0.6	2.8	2.1	0.2	0.1	9.5	3.6
22	210 237	208 363	1874	219	7.2	0.4	1.1	1.8	0.1	−0.1	7.1	2.2
23	74 562	72 800	1763	881	0.1	0.0	1.7	2.6	0.5	−0.1	0.0	3.2
24	100 567	97 297	3271	511	1.7	0.1	2.1	2.2	0.4	−0.8	0.8	3.1
25	34 657	33 834	823	1360	3.6	0.3	0.9	1.6	4.3	−0.6	3.0	4.7
26	42 025	41 888	138	1300	1.7	0.2	0.9	2.1	0.4	0.0	1.7	2.3
27	51 962	51 562	400	703	0.3	0.0	0.2	2.1	0.0	0.0	0.3	2.1
Total	12 123 881	12 071 309	52 572	20 653	35.9	1.3	6.2	11.7	7.3	−0.5	35.4	15.2

Appendix B: Northern Antarctic Peninsula net mass balance

Narrow deep fjords and steep spatial and temporal gradients in surface mass balance for the northern Antarctic Peninsula (B25–26) introduced large and poorly characterized uncertainties into estimates of ice discharge and $\sigma F_{\mathrm{d}v/\mathrm{d}t}$ that propagated to highly uncertain estimates of net mass change. For this reason, we derived our estimates of net mass change using previously published estimates from repeat surface elevation measurements that we added to our estimates of change in ice discharge. Work by Scambos et al. (2014), based on elevation changes, and recent gravity work (Harig and Simons, 2015) both suggest that the northern Antarctic Peninsula region (precise study extents vary) has seen continued mass losses at more or less a constant rate of 25–30 $\mathrm{Gt\,yr^{-1}}$ for the period 2003–2015; this is further supported by examination of JPL mascon (Watkins et al., 2015) mass anomalies and RACMO surface mass budget anomalies (See Fig. B1). Estimates based on CryoSat-2 (McMillan et al., 2014) suggest a reduced mass loss for B25 and B26 (below the significance level) for the period 2010–2013, but usable data from CryoSat-2 for this rugged region are sparse.

To estimate the net mass balance for basins B25 and B26, we used estimates of glacier mass loss determined from repeat elevation measurements for the 2003–2011 period as a starting point (Scambos et al., 2014). Since this study was restricted to areas north of 66° S, we added our estimate of change in ice discharge south of 66° S (6 $\mathrm{Gt\,yr^{-1}}$: Table 2) to estimate the basin-wide net mass balances for 2008–2015. The uncertainty in the net budget was calculated as the RSS of the uncertainty in the basin estimate of change in discharge, the uncertainty in the net balance estimated in Scambos et al. (2014) and the uncertainty in the surface mass budget. Basin totals and uncertainties are provided in Table 2.

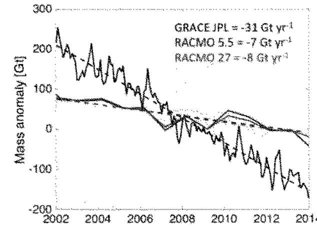

Figure B1. Rates of 2002–2014 mass change as derived from linear fits to cumulative anomalies of RACMO surface mass balance determined at 5.5 km (blue line) and 27 km (red line), and JPL V2.0 mascon anomalies (black line: http://grace.jpl.nasa.gov/data/get-data/jpl_global_mascons/) for the northern Antarctic Peninsula. Surface mass balance and JPL mascon anomalies were integrated for the seven mascons overlapping the northern Antarctic Peninsula (4324, 4325, 4372, 4373, 4374, 4415, 4416). For plotting purposes the surface mass balance anomalies were determined relative to the 1979–2003 mean. JPL mascons are corrected for changes in solid earth using the glacial isostatic adjustment (GIA) correction modeled by Geruo A and John Wahr. This figure is provided to support the argument for a relatively steady rate of northern Antarctic Peninsula mass change between the 2003 and 2015 and not to support the magnitude of that change, which is sensitive to the choice of the model used for the GIA correction.

Author contributions. ASG devised the study, developed the JPL auto-RIFT software, did all calculations and wrote the paper. GM was responsible for updating the grounding-line location and defining the flux gates, he also spent considerable time revising the manuscript after the lead author broke his wrist while snowboarding. TS and MF produced the LISA velocity fields; SL and MvdB provided modeled FAC and SMB output and JN produced surface elevation change rates from CryoSat-2 data. All authors discussed and commented on the manuscript at all stages.

Competing interests. The authors declare that they have no conflict of interest.

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